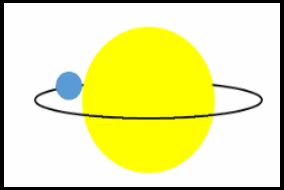


Exoplanet Observing with Small Telescopes

Dennis M. Conti
Chair, AAVSO Exoplanet Section
www.astrodennis.com

Objectives

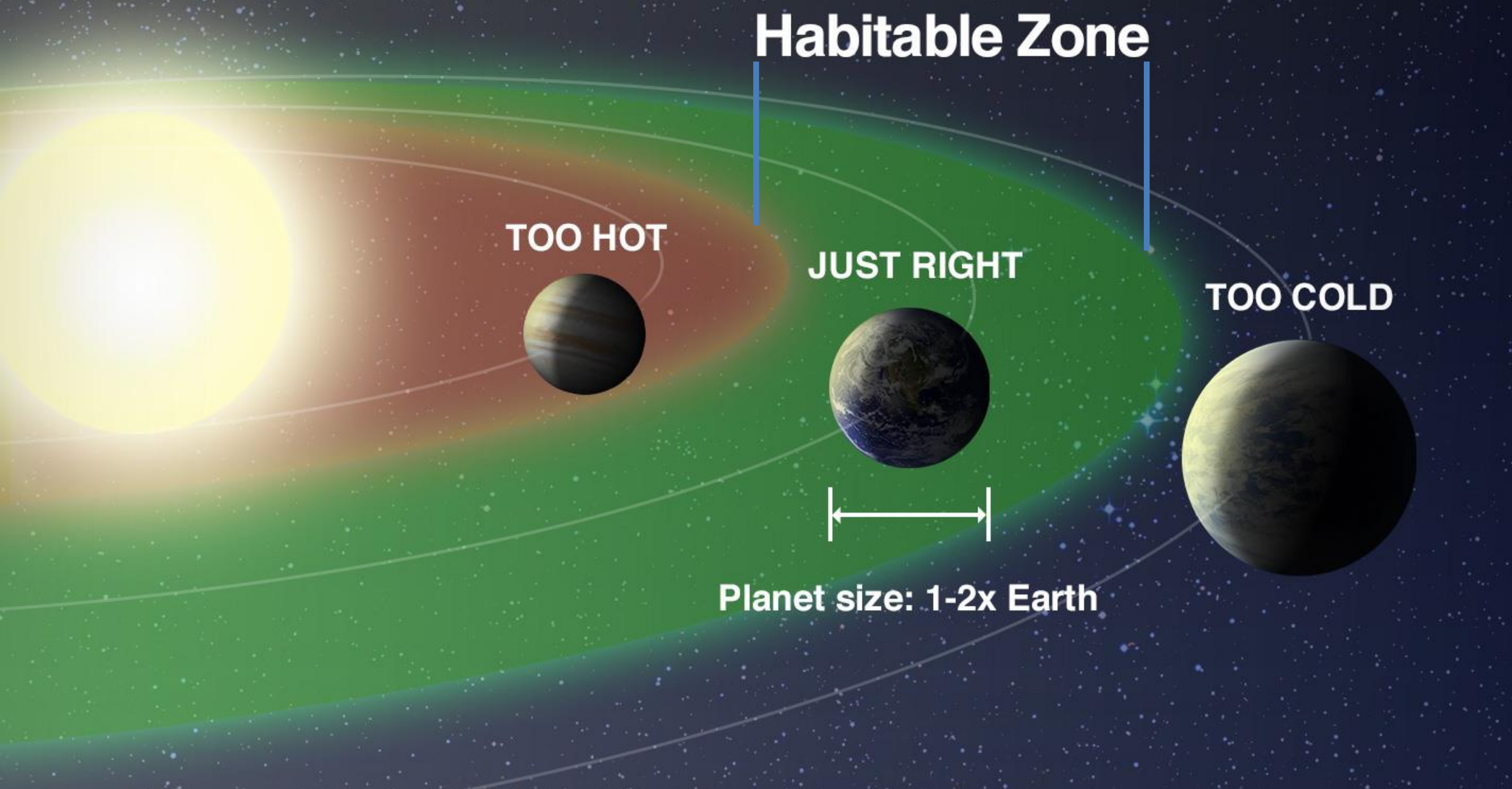
- Understand the fundamentals of high precision photometry and how they apply to exoplanet observing
- Learn “best practices” for exoplanet observing
- Be able to conduct an exoplanet observation and analyze the results
- Review what’s involved in publishing the results
- Discuss pro/am collaborations and the future of exoplanet observing by amateur astronomers

The Night Sky

Q: Which stars have one or more planets (exoplanets) around them?

A: Most of them!

The Kepler spacecraft has now confirmed that Earth-size planets exist in the habitable zone!



Courtesy: NASA

What is Driving Us?

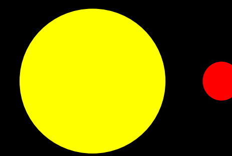
- How do planets form?

- How was our solar system formed?

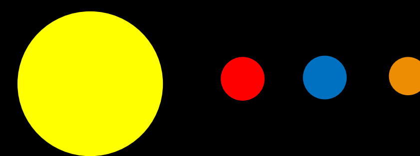
The ultimate goal:
detect biomarkers in the atmosphere
of planets in the habitable zone

The Strange World of “Other Worlds”

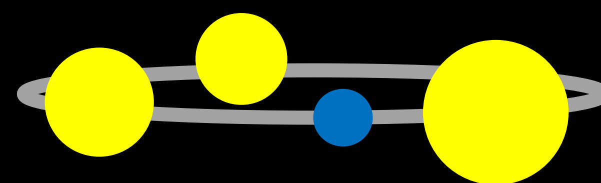
- Most exoplanets we have discovered are close-in, large planets: “Hot Jupiters”



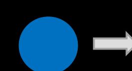
- Some stars have multiple planets



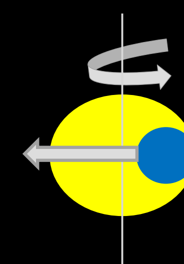
- Some planets orbit multiple stars



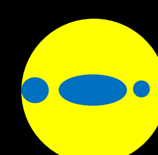
- Some “planets” are free-floating



- Some planets’ orbits are opposite from their star’s rotation



- Some planetesimals are disintegrating around their host star



History

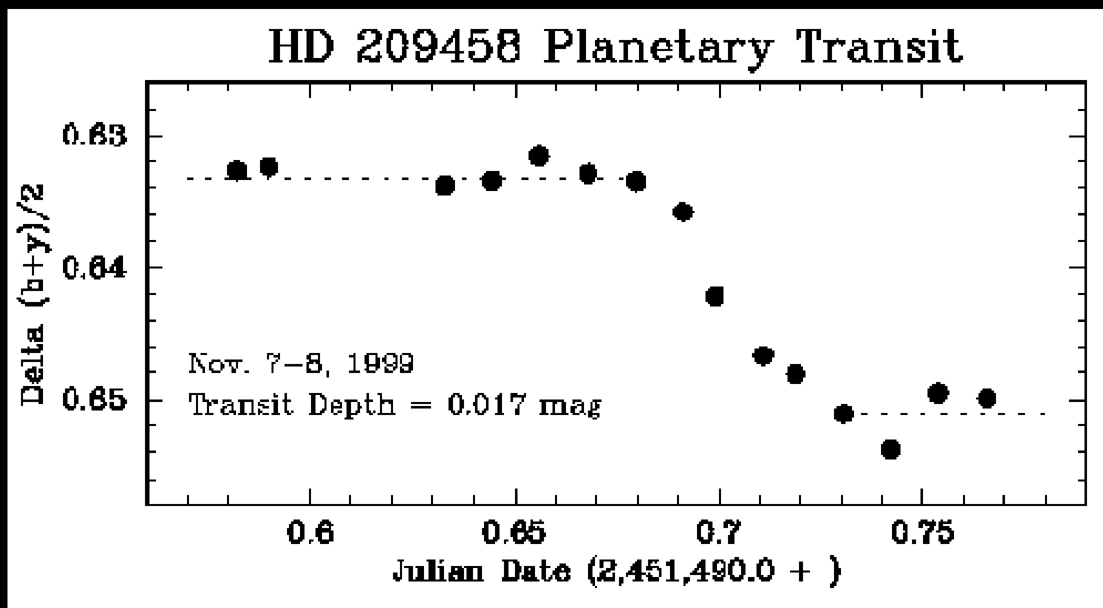
- 1917 – Carnegie Observatory astronomers (unknowingly) recorded evidence of an exoplanet; not realized until 2016
- 1992 – Aleksander Wolszczan and Dan Frail discovered an exoplanet around a pulsar
- 1995 – discovery of first exoplanet around a Sun-like star
- 1999 – detection of an exoplanet using a robotic telescope

Robotic Telescopes in the 1990s
ASP Conference Series, Vol. 34, 1992
Alex V. Filippenko (ed.)

THE USE OF ROBOTIC TELESCOPES FOR DETECTING PLANETARY SYSTEMS

WILLIAM J. BORUCKI
NASA Ames Research Center, Mail Stop 245-3, Moffett Field, CA 94035

RUSSELL M. GENET
Fairborn Observatory, 3435 E. Edgewood Ave., Mesa, AZ 85204



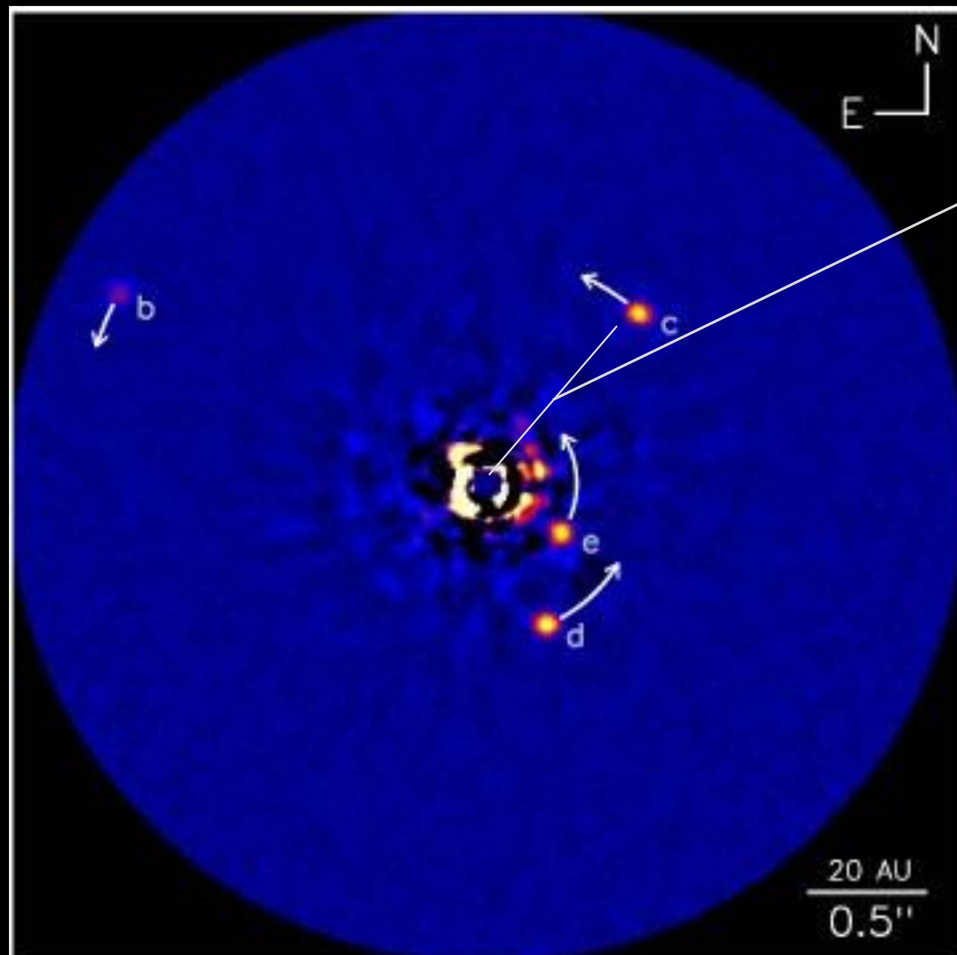
Courtesy Russ Genet

By the Numbers
(as of 10/21/16)

- 3,397 confirmed exoplanets
- 2,416 unconfirmed candidates
- 297 candidates in the habitable zone

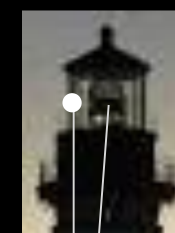
The Challenge

HR 8799



Courtesy: Keck Observatory

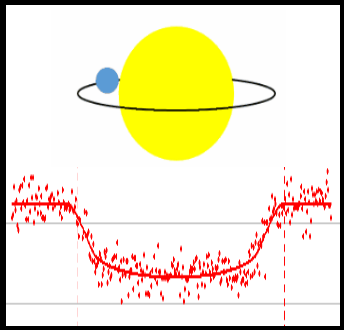
Equivalent to seeing the reflected light of a baseball that is ¼" from a lighthouse
1 mile away:



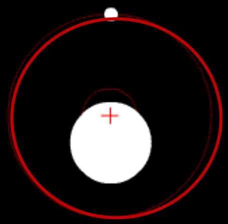
1 mile

Exoplanet Detection Methods

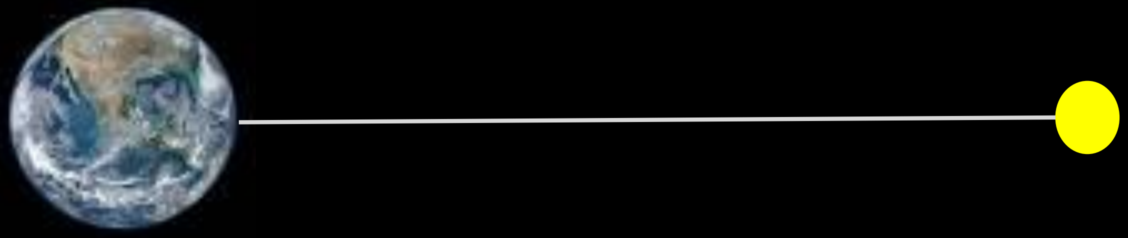
- Transit Method:
  - the dominant method used by amateur astronomers



- Radial Velocity Method

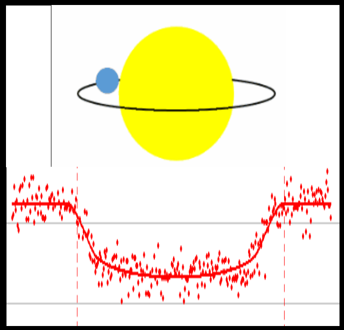


- Microlensing

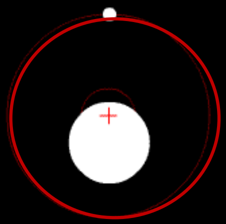


Exoplanet Detection Methods

- Transit Method:
  - the dominant method used by amateur astronomers



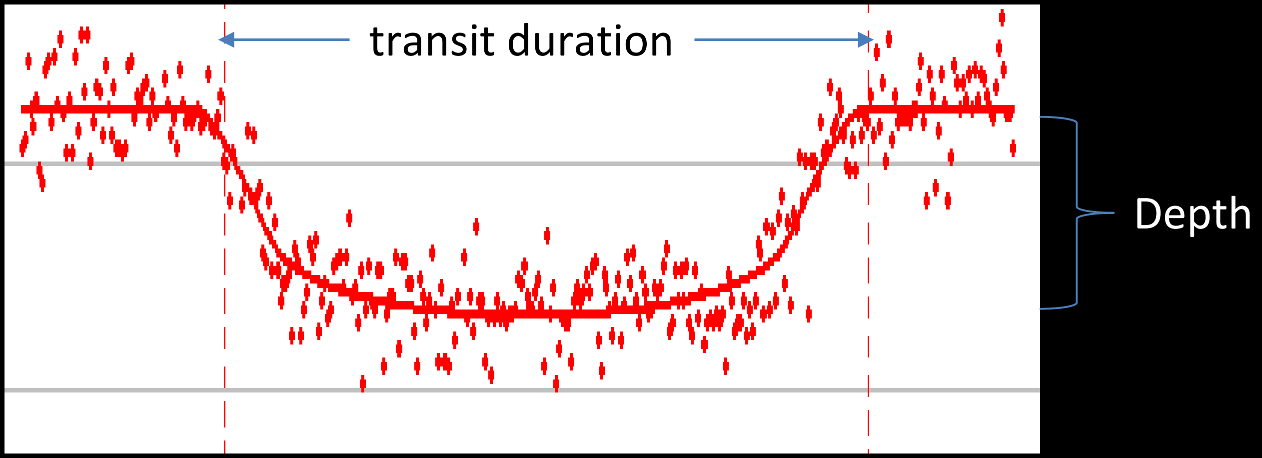
- Radial Velocity Method



- Microlensing

- Pulsations of Host Star
- Direct Imaging

The Light Curve



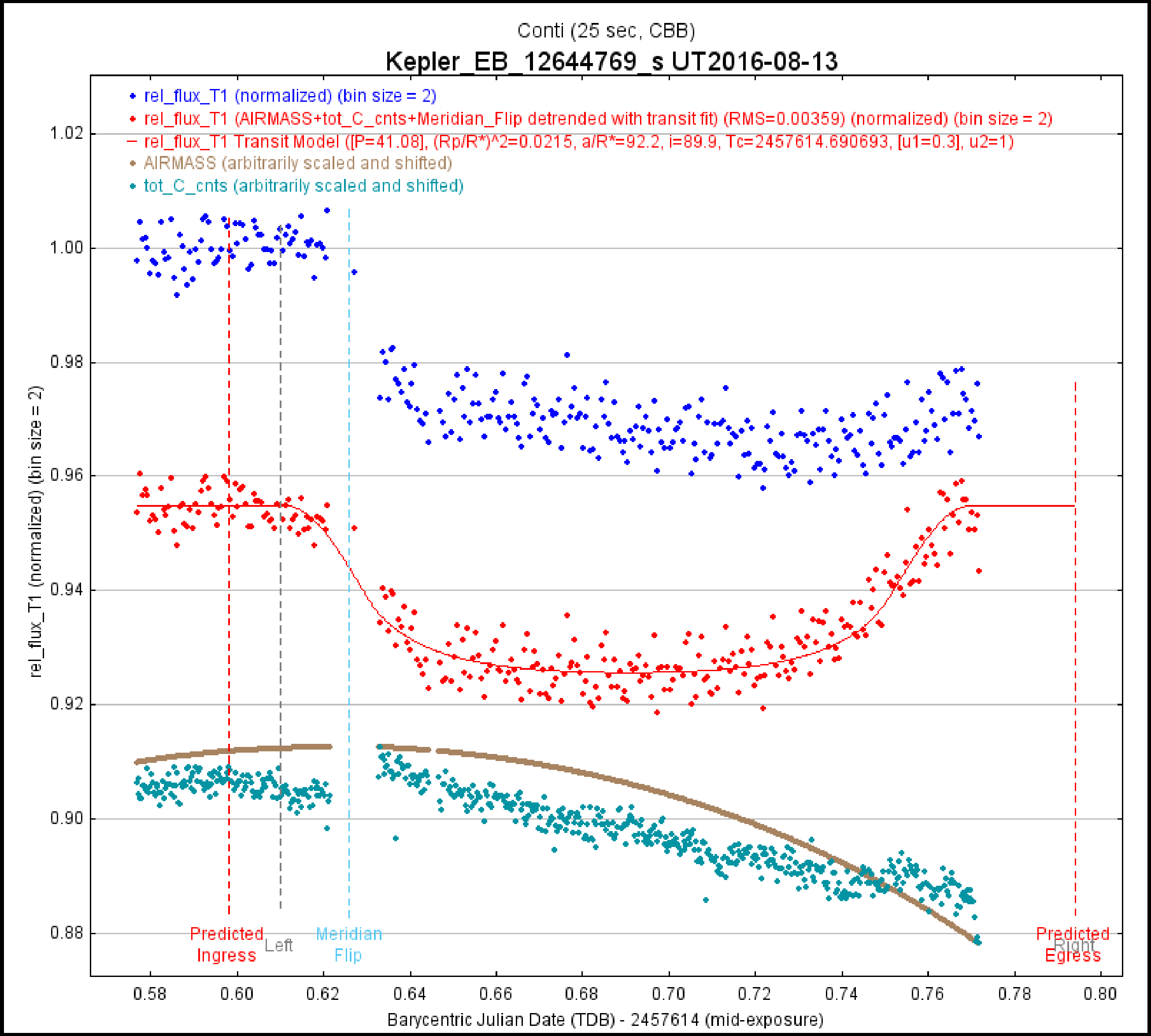
We can learn a lot just from the light curve!

- How big the planet is (its radius)
- How far it is from its host star (the size of its orbit)
- How inclined is its orbit from our line-of-sight
- Whether it is truly a planet or another star

Detecting Eclipsing Binaries vs. Exoplanets

- An eclipsing binary will most often show different light curve depths with different filters
- The light curve of an eclipsing binary is often much deeper than that of an exoplanet

Example: Eclipsing Binary Light Curve



Star/Planet Properties and Relationships

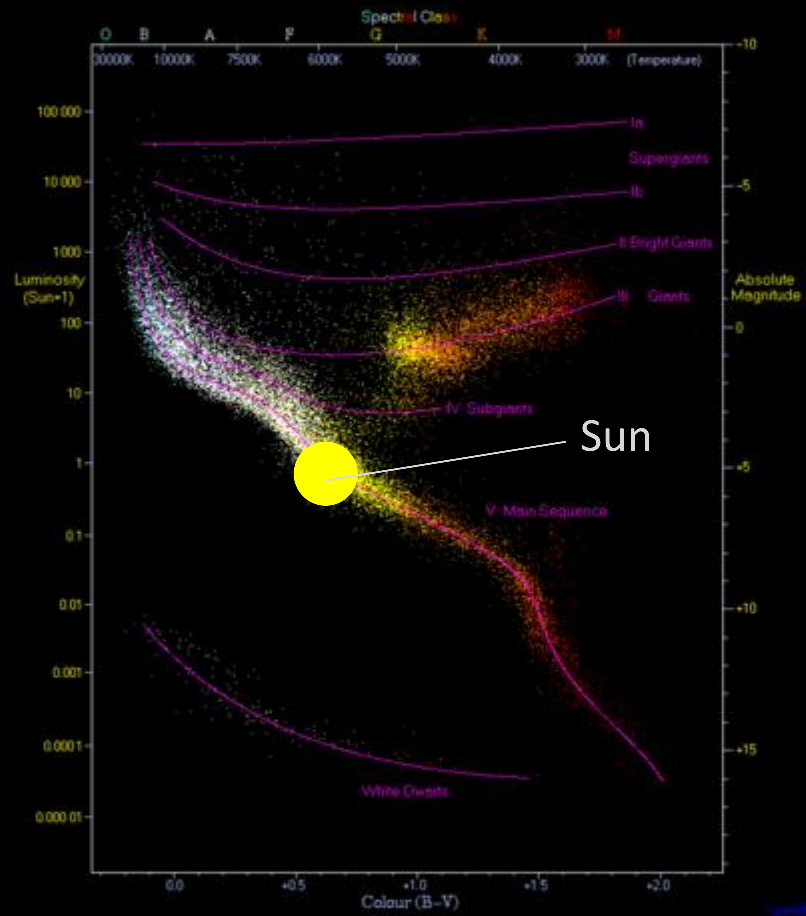
Notation Conventions

- Star parameters:
  - M_* - mass relative to the mass of the Sun ($M_{sun} = M_\odot$)
  - R_* - radius relative to the radius of the Sun ($R_{sun} = R_\odot$)
  - L_* - luminosity relative to that of the Sun ($L_{sun} = L_\odot$)
  - T_* - temperature relative to that of the Sun ($T_{sun} = T_\odot$)

- Planetary parameters:
  - M_p – mass relative to the mass of Jupiter (M_{jup})
  - R_p - radius relative to the radius of Jupiter (R_{jup})

- Transit parameters:
  - T_c - midpoint of a transit
  - F - flux
  - P - orbital period
  - a - semi-major axis (in astronomical units – AUs)

Hertzbrung-Russell (H-R)Diagram



- Actual luminosity L_* = a function of temperature (spectral type)

Star Radius, Luminosity and Temperature

- Radius-Luminosity-Temperature Relationship:

  Star radius $R_* = \sqrt{L_* / T_*^4}$,where:

  L_* = actual luminosity

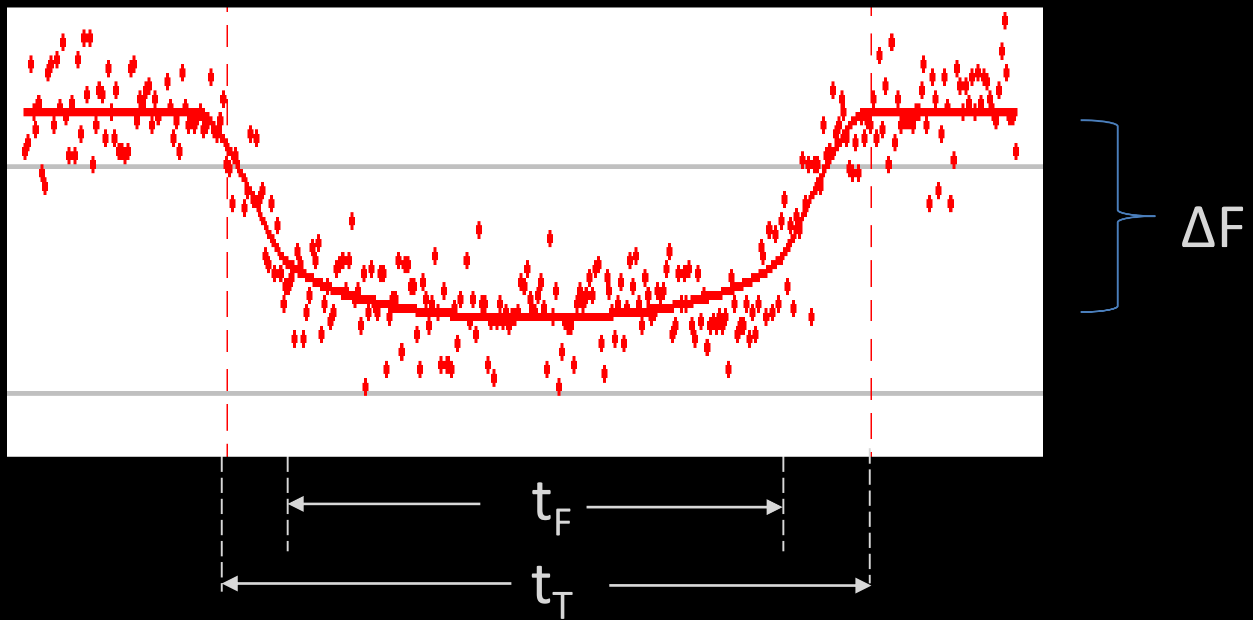
  T_* = temperature

- R_* will later be used to compute exoplanet properties

- Mass-Luminosity Relationship (for main sequence stars):

  Star mass $M_* = \sqrt[3.5]{(L_* \cdot M_{sun}^{3.5}/L_{sun})}$

Exoplanet Properties from Primary Eclipse

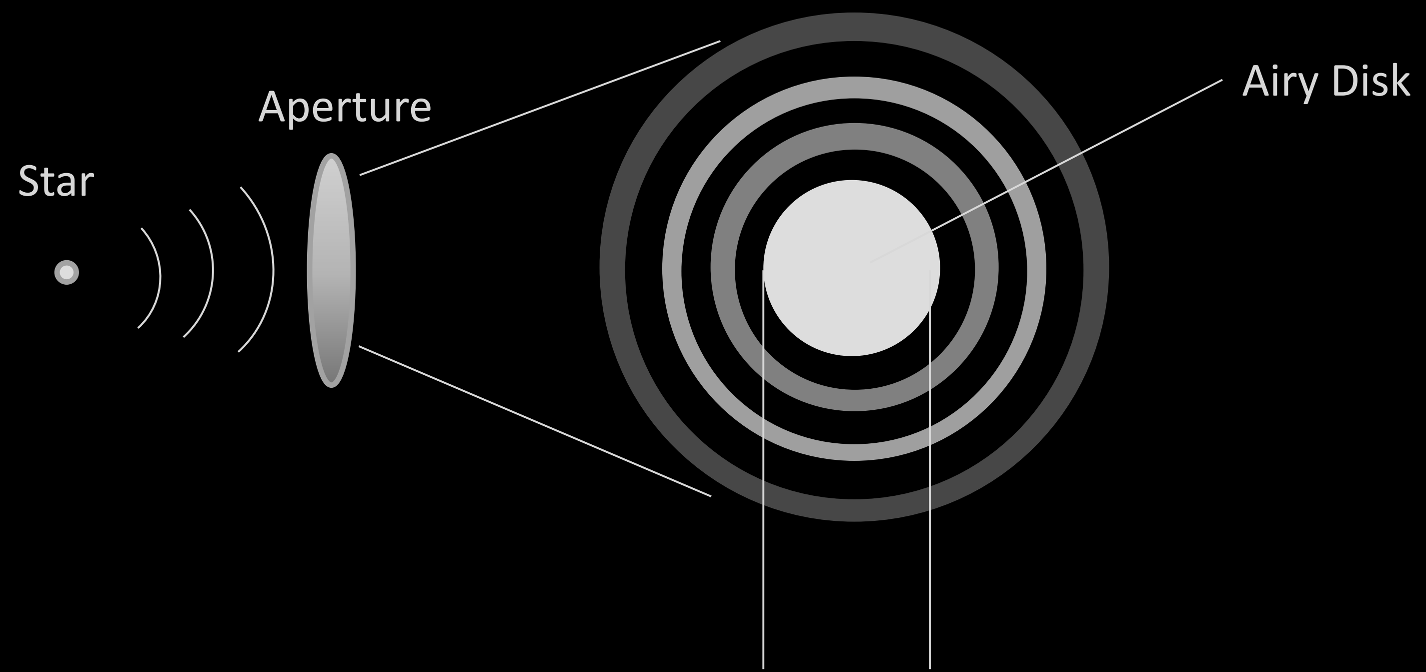


- Exoplanet radius: $R_p = f_1(R_*, \Delta F)$
- Exoplanet orbit : $a/R_* = f_2(P, \Delta F, t_T, t_F)$
- Exoplanet orbit inclination: $i = f_3(P, \Delta F, t_T, t_F)$

(see Seager, et al. 2002)

Fundamentals of High Precision Photometry

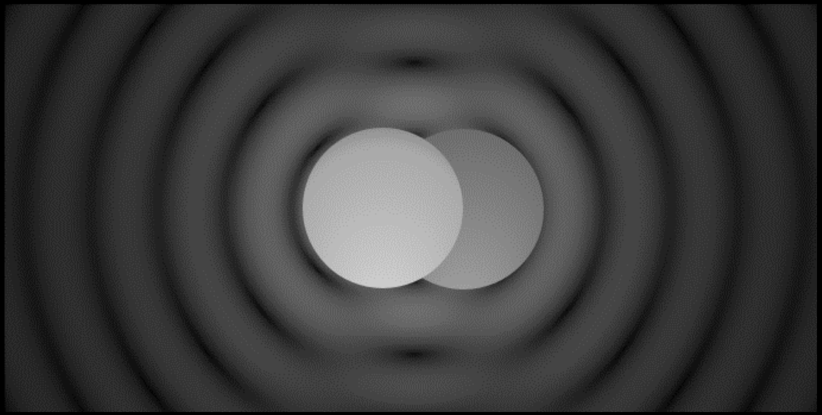
Point Spread Function (PSF)



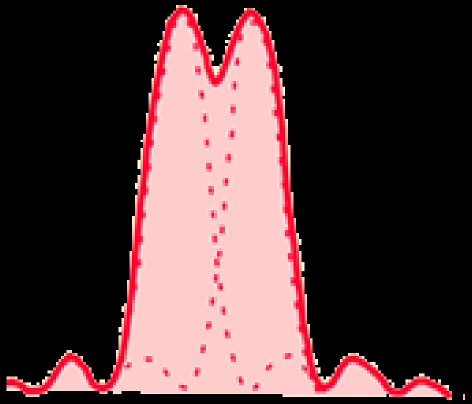
2.44*wavelength/aperture diameter

For an 11” scope at 656 nm = 1.2 arcseconds

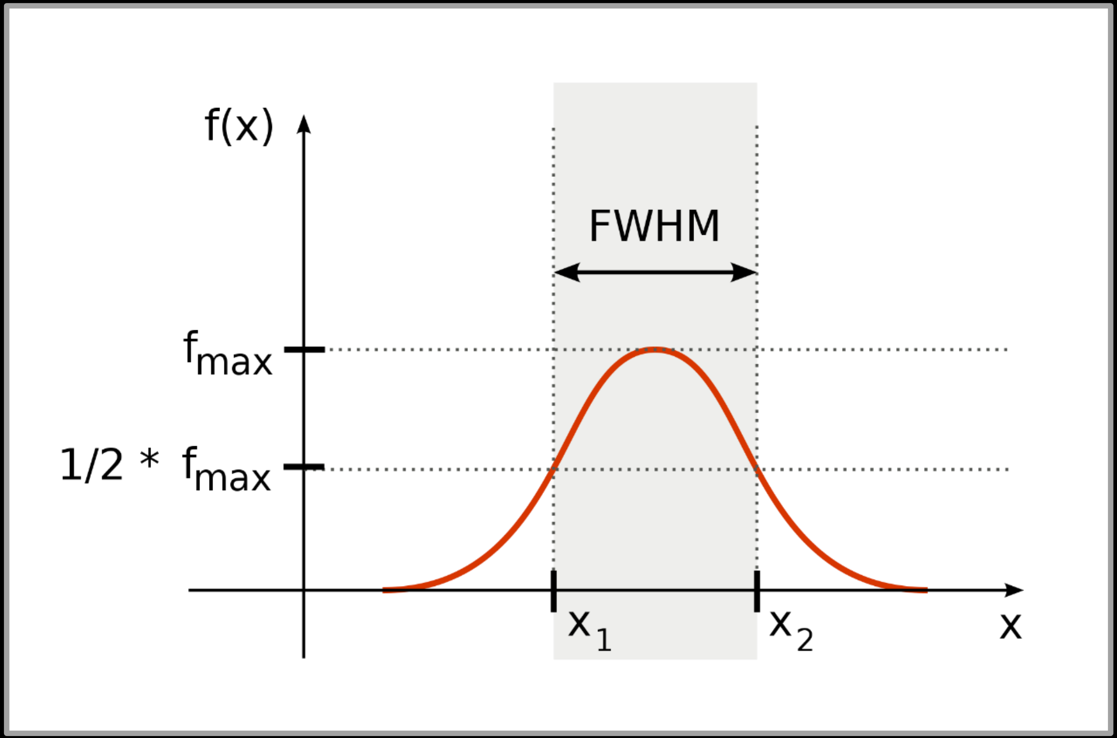
Resolution:
Raleigh Criterion



By Spencer Bliven - Own work, Public Domain,
https://commons.wikimedia.org/w/index.php?curid=31456019



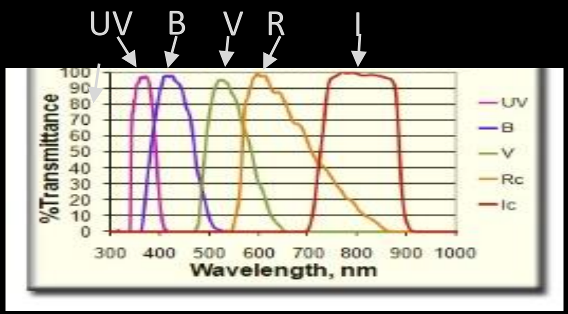
Full Width at Half Maximum (FWHM)



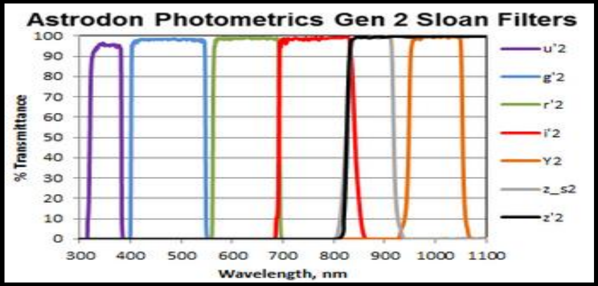
- Used as a measure of "seeing"

Bandpass Filters

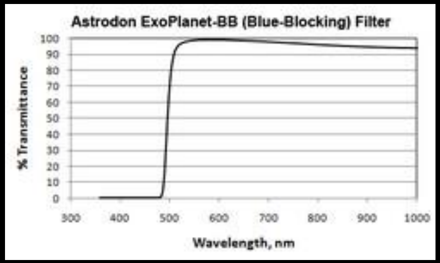
- Standard photometric filters (preferred for exoplanet work):
  - Johnson-Cousins:



  - Sloan Digital Sky Survey (SDSS):

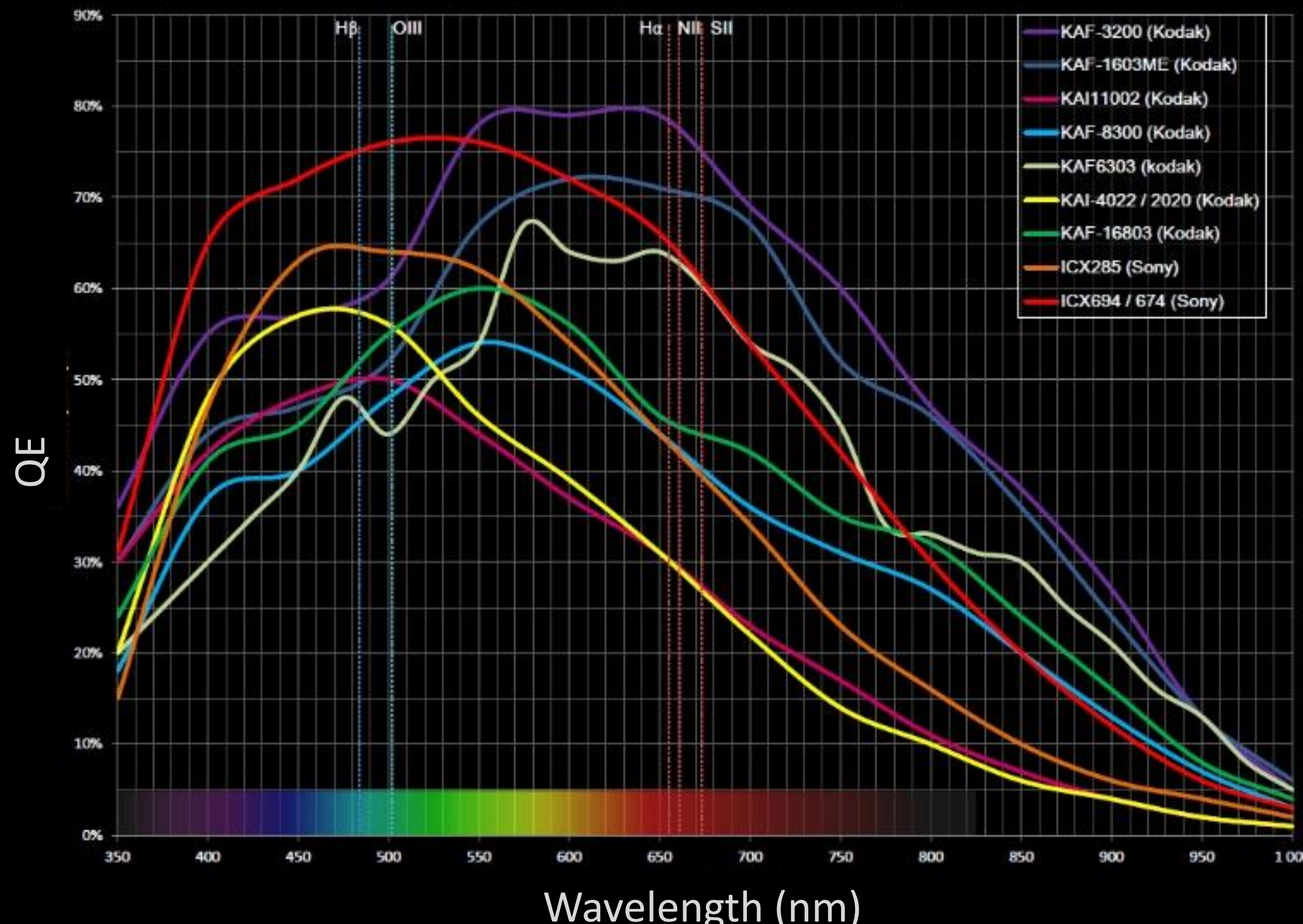


  - "Exoplanet" Filter: (Clear Blue Blocking)



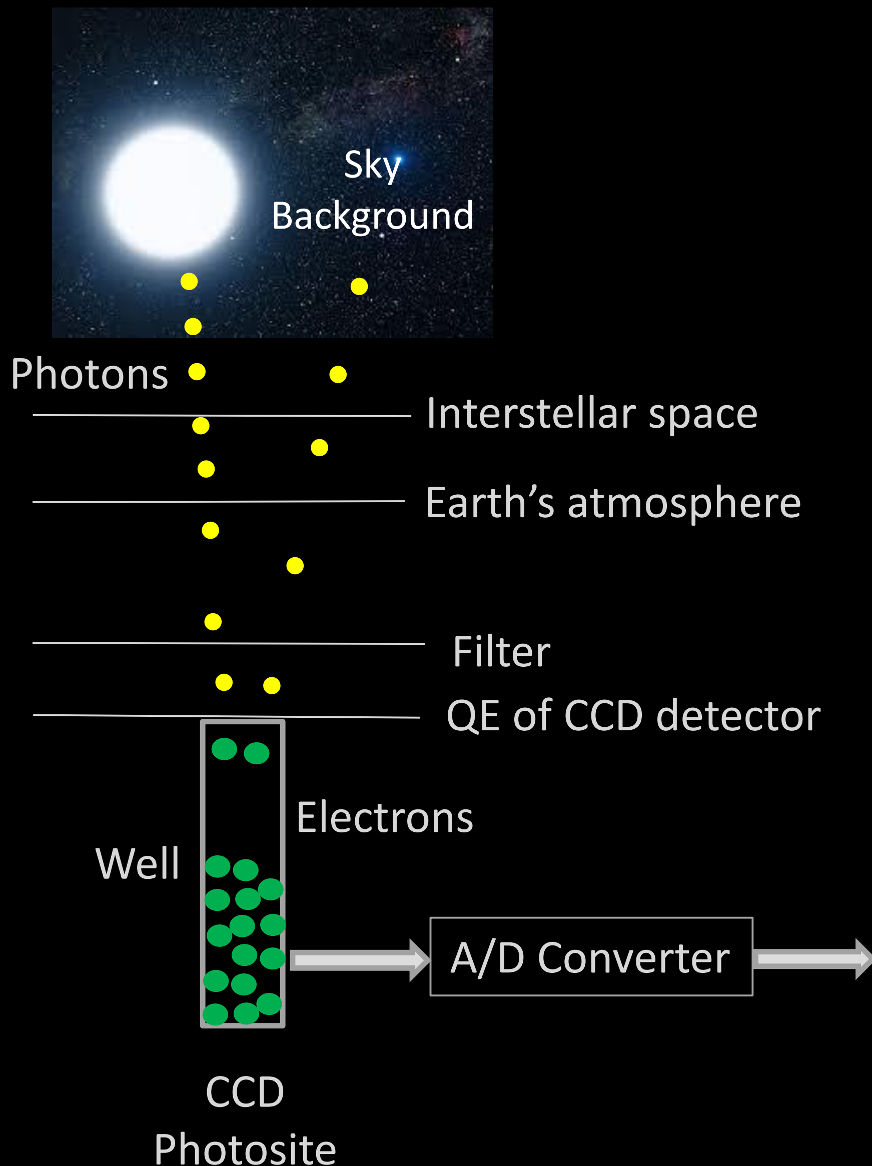
Courtesy: Astrodon

Quantum Efficiency (QE) of a CCD Detector



By Philippe Bernhard

It’s all about counting photons!



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

A Star’s Centroid

- Centroid: the “center of gravity” of a star whose light is spread across many pixels

- Important in determining the distance between star images on a CCD detector and in performing aperture photometry

- Not a trivial process: begins with determining which pixels are “part of the star”

ADU Readings (13 x 13 pixels)

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
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593	768	1164	2195	4307	6910	9001	10074	7753	5251	2890	1713	1066	625
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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
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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

Flux vs. Magnitude

- Flux = energy detected per area per second
- Apparent magnitude = measure of a star's brightness as seen from Earth
  - It is relative to a reference and is particular to a wavelength
  - $m_1 = m_{ref} - 2.5 \log (f_1/f_{ref})$
  - A difference of 5 magnitudes = 100 times as much brightness:
    Example, for f_1=1000, f_{ref}=10, and m_{ref} = 12:

$$
\begin{aligned}
m_1 &= 12 - 2.5 \log (1000/10) \\
&= 12-5 \\
&= 7
\end{aligned}
$$

- Absolute magnitude = a measure of a star's brightness as seen as if we were 10 parsecs (32.6 light years away)
- ADUs are sometimes used as a proxy for flux

Equipment and Software Related to Exoplanet Observing

Typical Setup
Location: Suburban Annapolis, MD

Characteristics of a CCD Camera

- Gain (electrons/ADU)
- Read noise (electrons)
- Dark current (electrons/pixel/second)
- Size of pixels (in microns)
- Number of pixels
- Quantum efficiency

Sources of Signal and Noise

- Signals:
  - Detected photons: photons that translate to ADU counts
  - Dark current: an unwanted signal that is a function of exposure time
  - Bias: a constant offset to ADU count

- Noise:
  - Shot noise – uncertainty in photon counts
  - Dark current noise – uncertainty in dark current
  - Readout noise – uncertainty in read noise

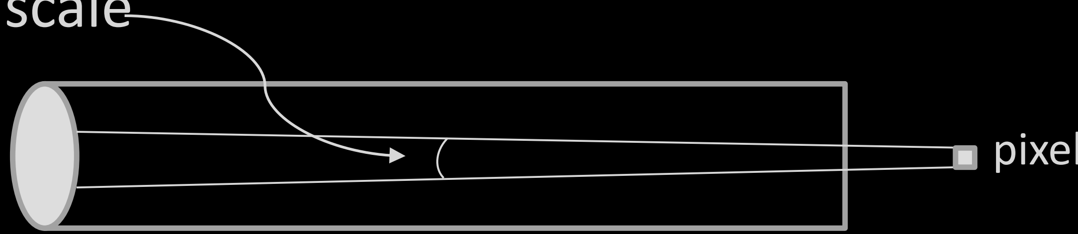
<u>Key</u>: increase signal, reduce noise

Optical Tube Assembly (OTA) Characteristics

- Type of OTA – e.g., Schmidt-Cassegrain, Reflector, Refractor, etc.
- Aperture
- Focal length
- Central obstruction(s)
- Thermal characteristics
- Focusing accuracy
- Collimation
- Spherical aberration

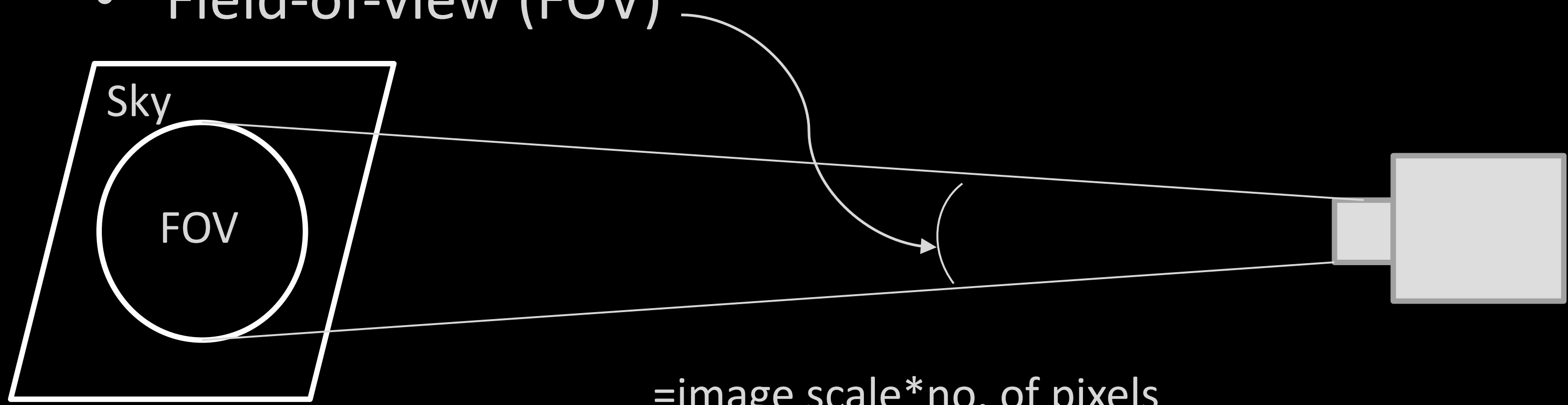
Image Characteristics

- Image scale



=206.265*pixel size(microns)/focal length(mm)

- Field-of-view (FOV)

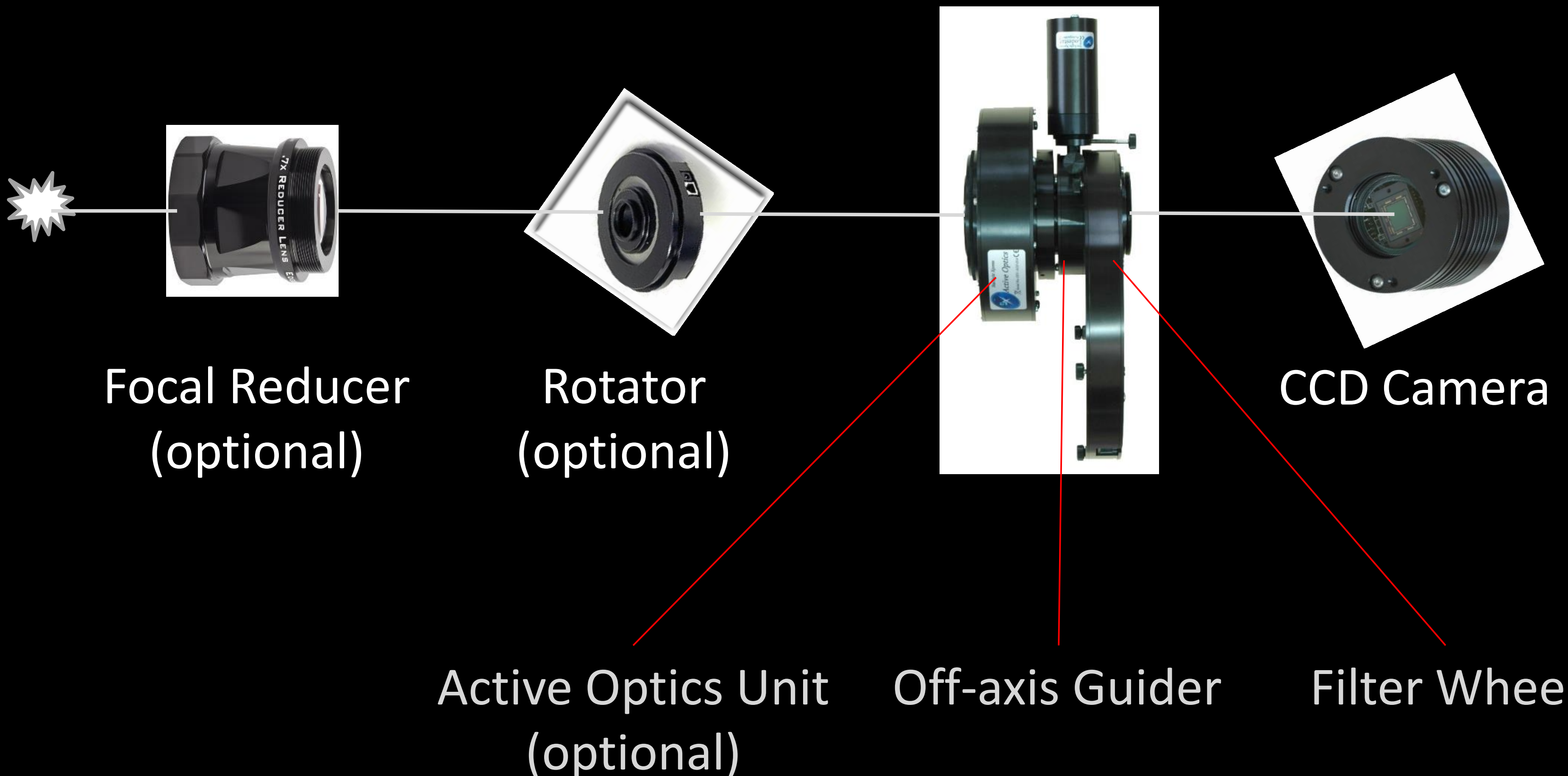


=image scale*no. of pixels

Mount Characteristics

- Type of mount – e.g., German Equatorial Mount, fork mount, alt-az mount
- Periodic error in RA
- DEC backlash
- Balance
- Polar alignment accuracy

Imaging Chain



Autoguiding

- Approaches:
  - Use of a guide scope – could result in flexure
  - Off-axis guiding
  - On-camera guide chip
  - On-axis guider

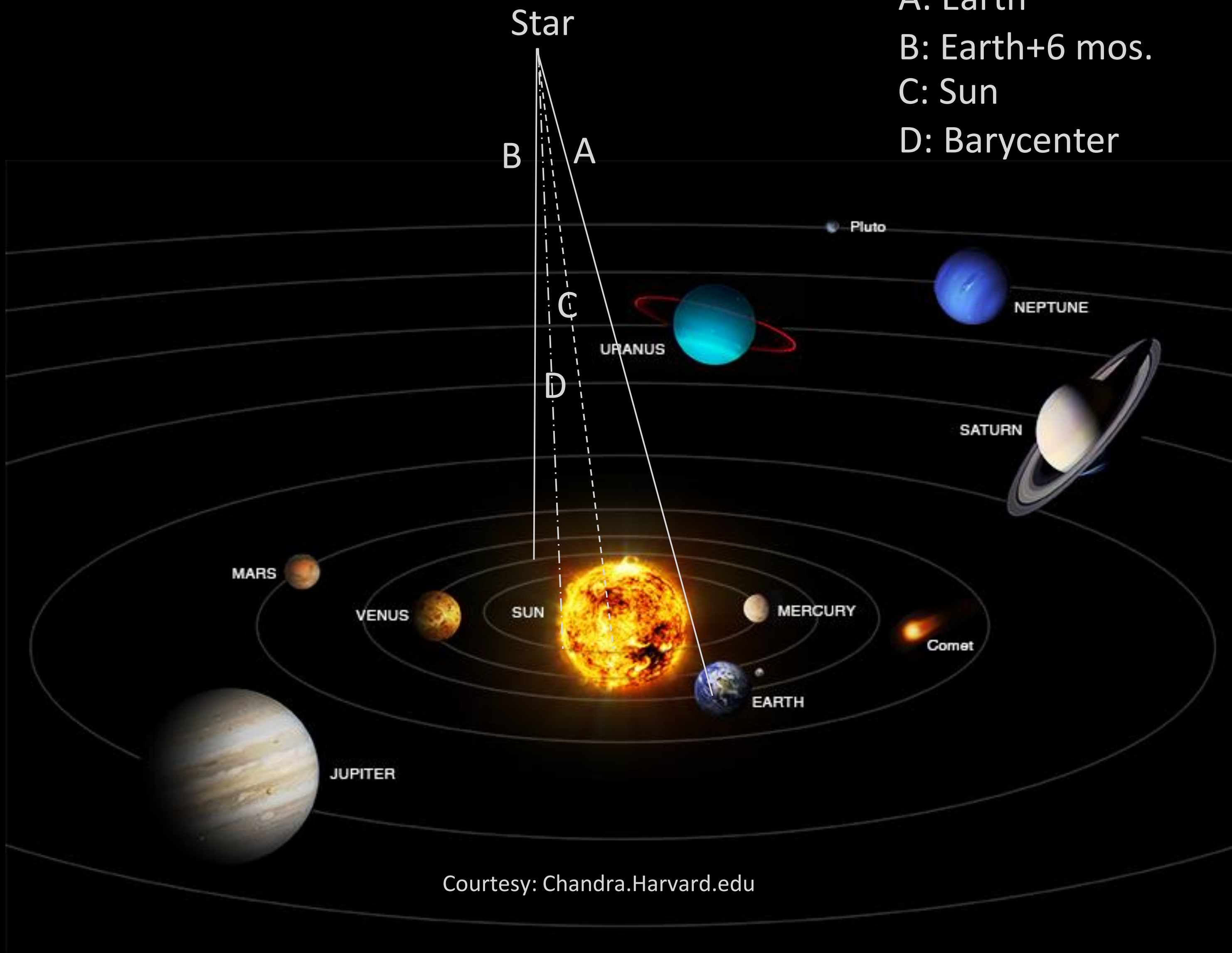
- All approaches use a (preferably sensitive) guide camera

- Mount control: ideally via ASCOM pulse guiding

- Software:
  - requires initial calibration
  - some software will automatically correct for changes in DEC and side-of-pier
  - Popular ones: PHD2, SkyX Pro, Maxim DL

Reference Locations

A: Earth
B: Earth+6 mos.
C: Sun
D: Barycenter



Courtesy: Chandra.Harvard.edu

What time is it?

Time base = reference location and time standard (clock)

- Local time at San Diego, CA: 13:00 on October 29, 2016
- UTC time at Greenwich, England: 20:00 on October 29, 2016
- JD (above in Julian Date form): 2457691.33333

$\downarrow$ +6.4 min.

- HJD_{UTC} (Heliocentric Julian Date, UTC) for Kelt-1 at (00h 01m 26.92s, 39°23'01.7") 2457691.33780

$\downarrow$ +1.1 min.

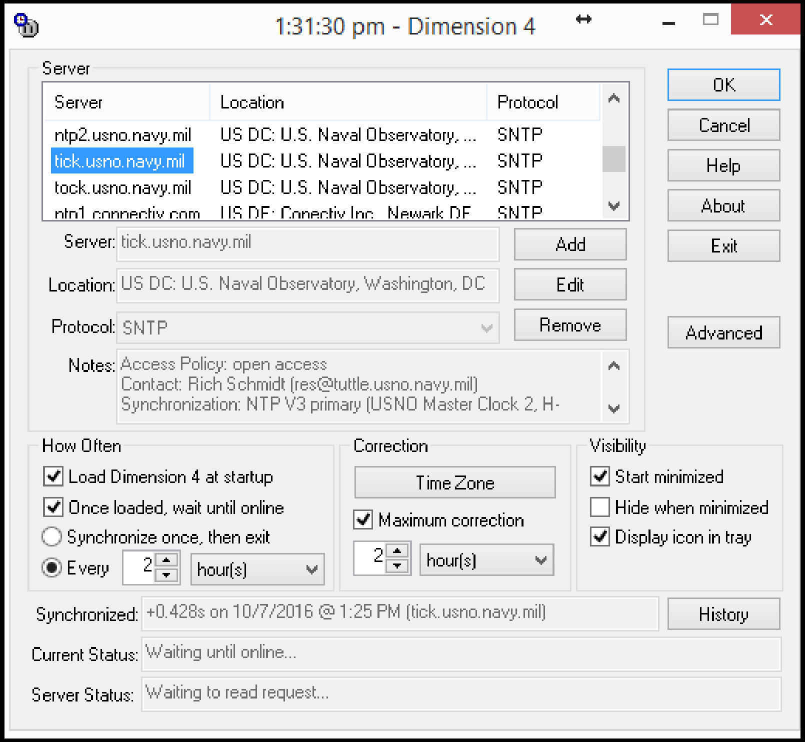
- BJD_{TDB} (Barycentric Julian Date, Barycentric Dynamical Time) for Kelt-1 and 32:36:48N, 116:19:55W, 1131m alt. 2457691.33858

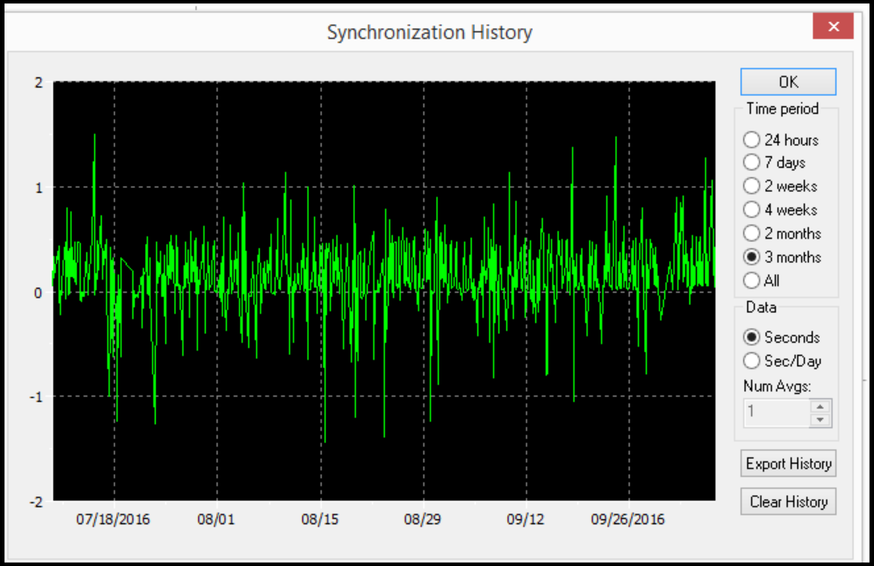
It is important to…

- …know in what time base are the predicted transit times
- ..use the appropriate time base for exoplanet transit results

Overcoming Time Drift in Image Capture Computer

- Need to periodically update image capture computer clock to synchronize it with atomic clock
- Popular freeware to do this: Dimension 4





How do Amateur Astronomers Create Light Curves?

- Comparison stars in the same field-of-view as the host star are used to distinguish a true transit from a common event, such as high cirrus clouds

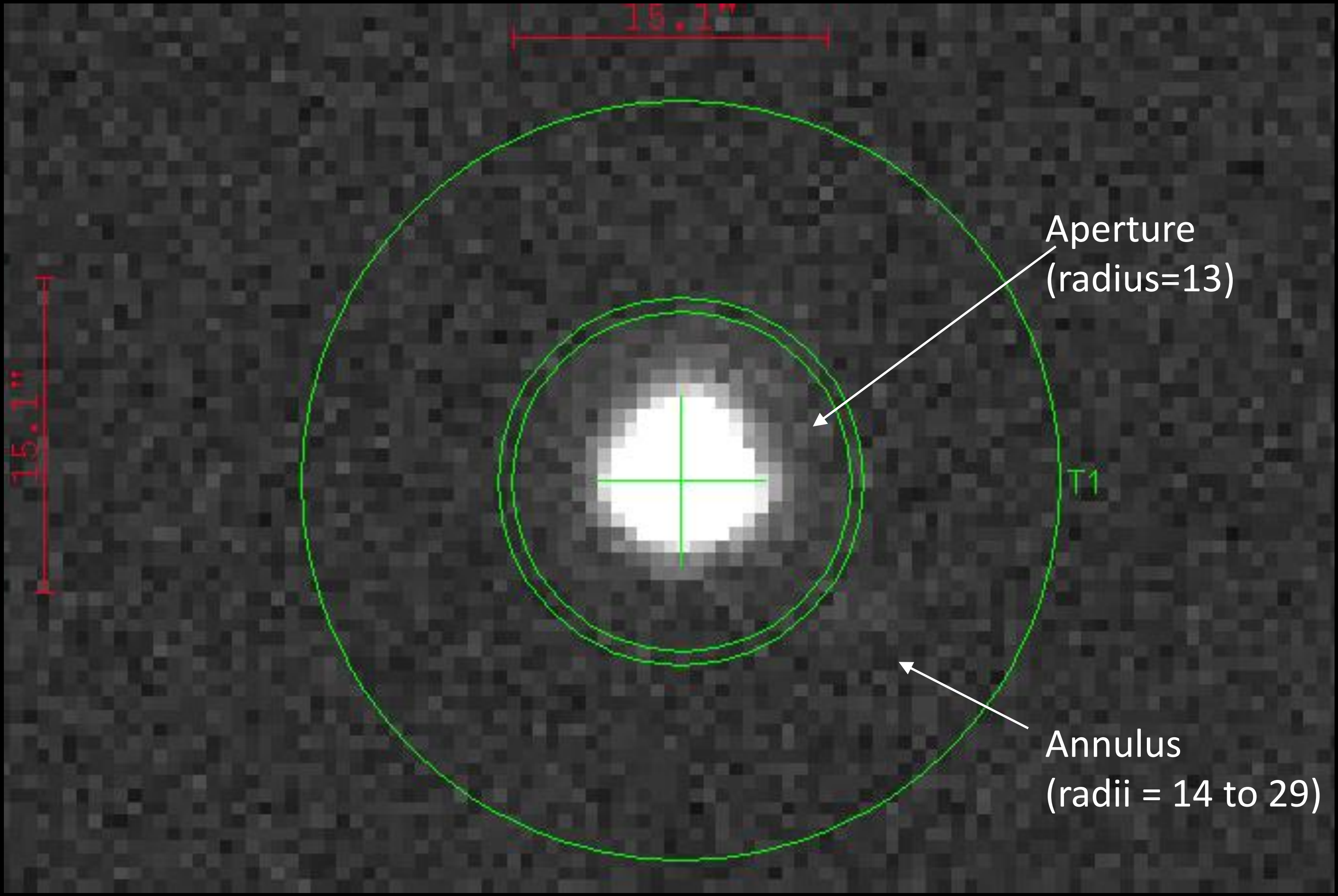
- <u>Aperture photometry</u> is used to measure the brightness of each star, with compensation for background sky glow due to light pollution, moon light, etc.

- <u>Differential photometry</u> then compares the relative change in light between the host star and the comparison stars

- 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 Aperture Photometry: the Aperture and Annulus



Online Resources

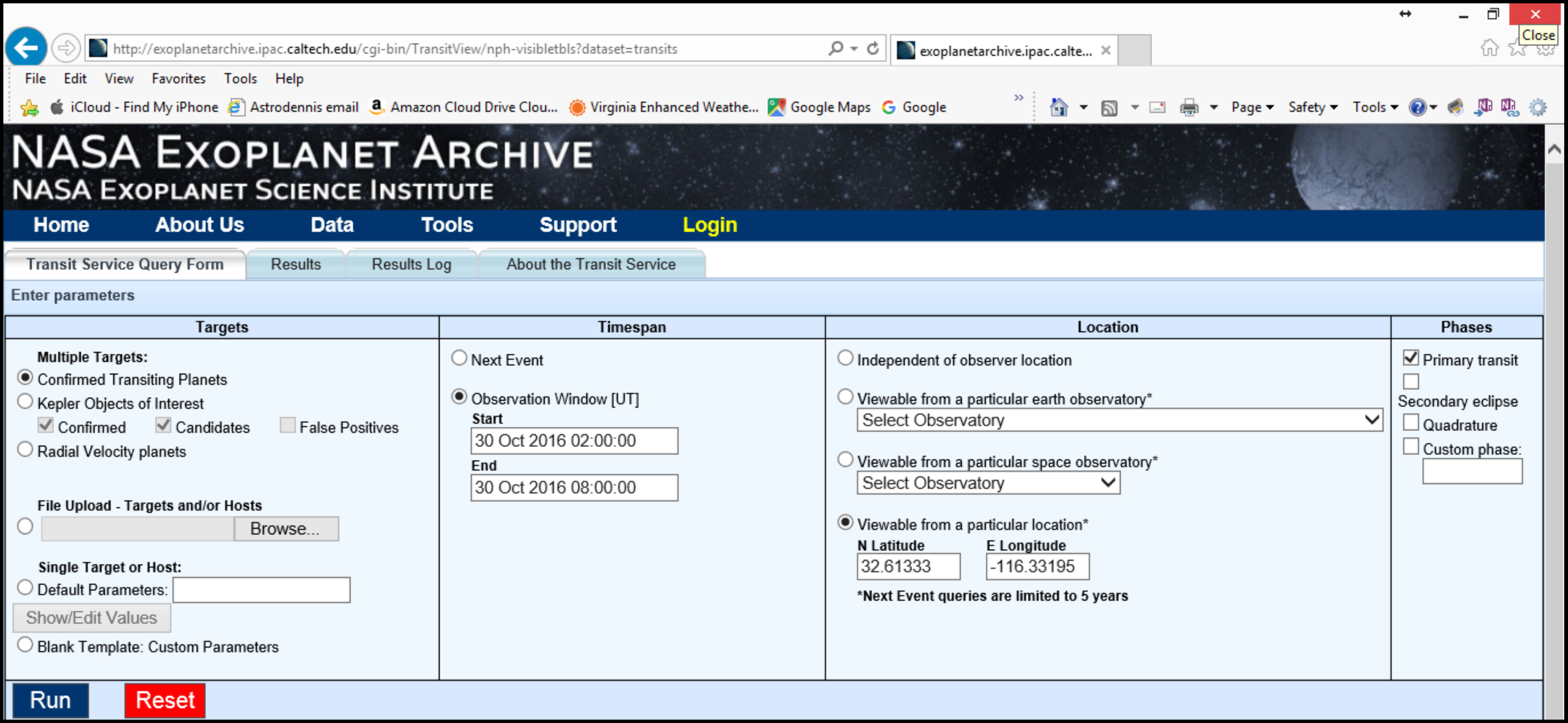
Time Conversions

- Local time to JD_{UTC} :
  http://www.onlineconversion.com/julian_date.htm

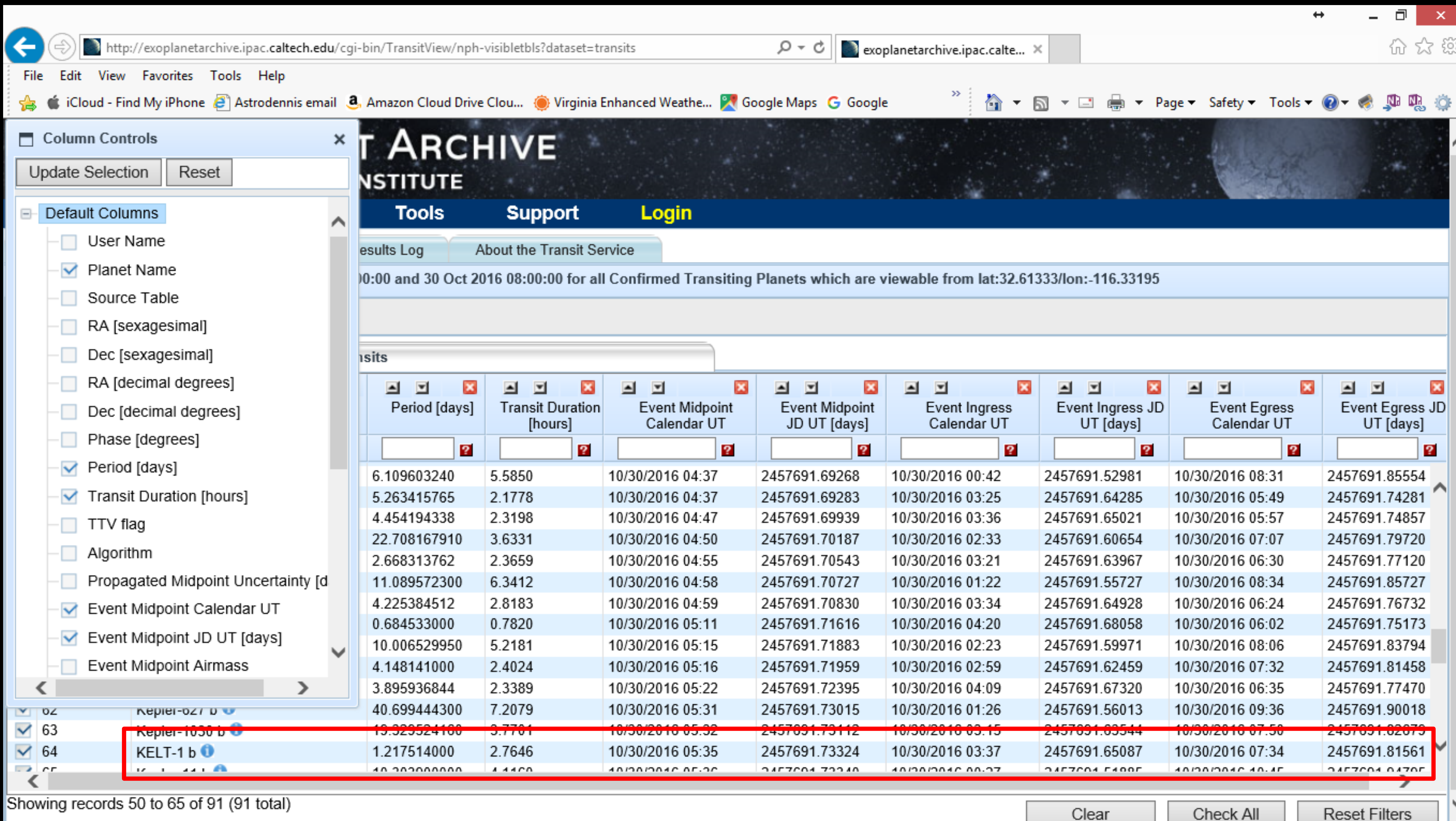
- JD_{UTC} to BJD_{TDB} :
  http://astroutils.astronomy.ohio-state.edu/time/utc2bjd.html

Exoplanet Information

- NASA Exoplanet Archive:
  http://exoplanetarchive.ipac.caltech.edu/cgi-bin/TransitView/nph-visibletbls?dataset=transits

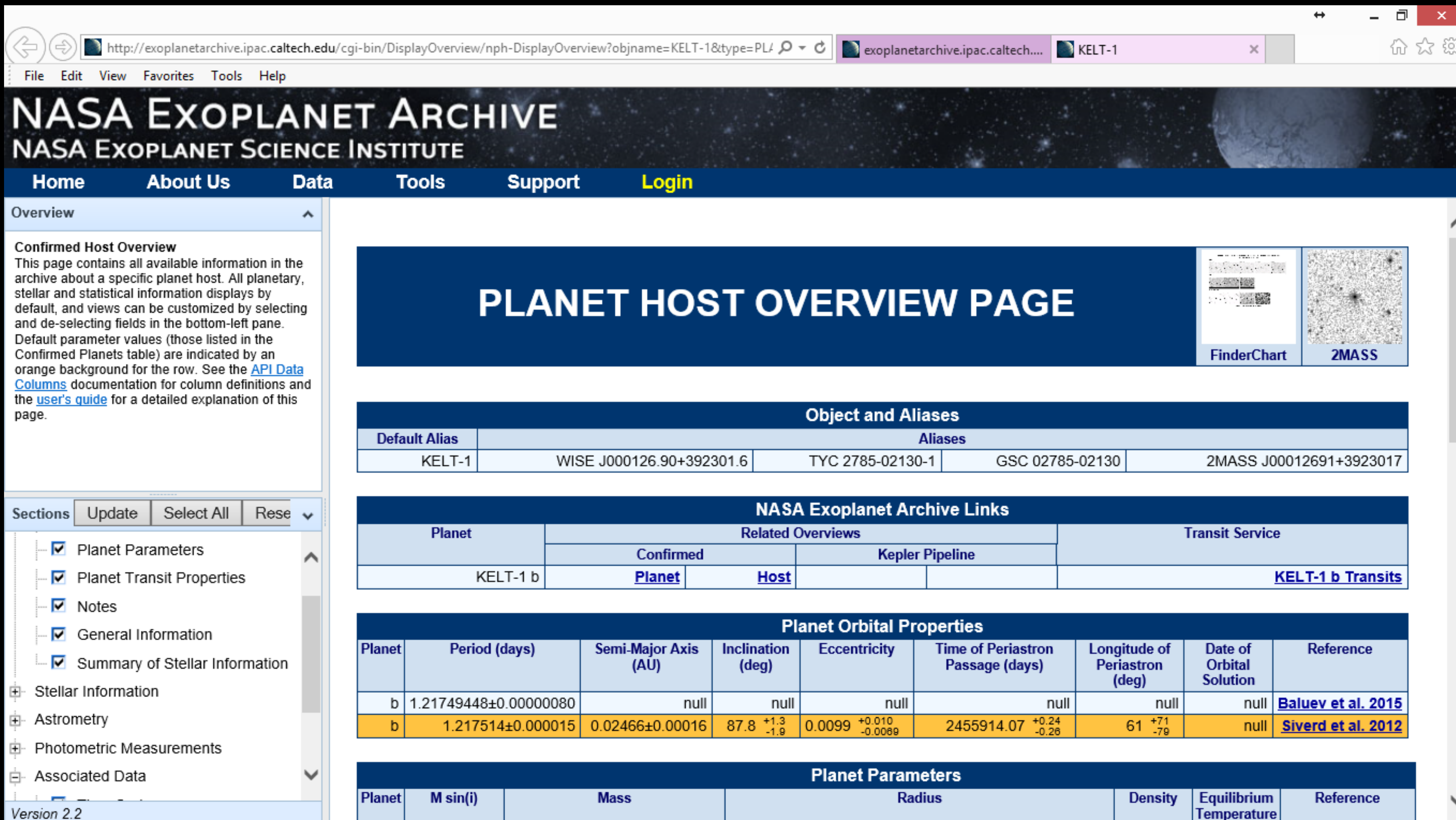


Exoplanet Information (cont'd)



Period [days]	Transit Duration [hours]	Event Midpoint Calendar UT	Event Midpoint JD UT [days]	Event Ingress Calendar UT	Event Ingress JD UT [days]	Event Egress Calendar UT	Event Egress JD UT [days]
6.109603240	5.5850	10/30/2016 04:37	2457691.69268	10/30/2016 00:42	2457691.52981	10/30/2016 08:31	2457691.85554
5.263415765	2.1778	10/30/2016 04:37	2457691.69283	10/30/2016 03:25	2457691.64285	10/30/2016 05:49	2457691.74281
4.454194338	2.3198	10/30/2016 04:47	2457691.69939	10/30/2016 03:36	2457691.65021	10/30/2016 05:57	2457691.74857
22.708167910	3.6331	10/30/2016 04:50	2457691.70187	10/30/2016 02:33	2457691.60654	10/30/2016 07:07	2457691.79720
2.668313762	2.3659	10/30/2016 04:55	2457691.70543	10/30/2016 03:21	2457691.63967	10/30/2016 06:30	2457691.77120
11.089572300	6.3412	10/30/2016 04:58	2457691.70727	10/30/2016 01:22	2457691.55727	10/30/2016 08:34	2457691.85727
4.225384512	2.8183	10/30/2016 04:59	2457691.70830	10/30/2016 03:34	2457691.64928	10/30/2016 06:24	2457691.76732
0.684533000	0.7820	10/30/2016 05:11	2457691.71616	10/30/2016 04:20	2457691.68058	10/30/2016 06:02	2457691.75173
10.006529950	5.2181	10/30/2016 05:15	2457691.71883	10/30/2016 02:23	2457691.59971	10/30/2016 08:06	2457691.83794
4.148141000	2.4024	10/30/2016 05:16	2457691.71959	10/30/2016 02:59	2457691.62459	10/30/2016 07:32	2457691.81458
3.895936844	2.3389	10/30/2016 05:22	2457691.72395	10/30/2016 04:09	2457691.67320	10/30/2016 06:35	2457691.77470
40.699444300	7.2079	10/30/2016 05:31	2457691.73015	10/30/2016 01:26	2457691.56013	10/30/2016 09:36	2457691.90018
1.217514000	2.7646	10/30/2016 05:35	2457691.73324	10/30/2016 03:37	2457691.65087	10/30/2016 07:34	2457691.81561

Exoplanet Information (cont'd)


http://exoplanetarchive.ipac.caltech.edu/cgi-bin/DisplayOverview/nph-DisplayOverview?objname=KELT-1&type=PL/

exoplanetarchive.ipac.caltech.... | KELT-1

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Sections | Update | Select All | Rese

- Planet Parameters
- Planet Transit Properties
- Notes
- General Information
- Summary of Stellar Information
- Stellar Information
- Astrometry
- Photometric Measurements
- Associated Data

Version 2.2

PLANET HOST OVERVIEW PAGE

FinderChart | 2MASS

Object and Aliases

Default Alias	Aliases			
KELT-1	WISE J000126.90+392301.6	TYC 2785-02130-1	GSC 02785-02130	2MASS J00012691+3923017

NASA Exoplanet Archive Links

Planet	Related Overviews				Transit Service
	Confirmed		Kepler Pipeline		
KELT-1 b	Planet	Host			KELT-1 b Transits

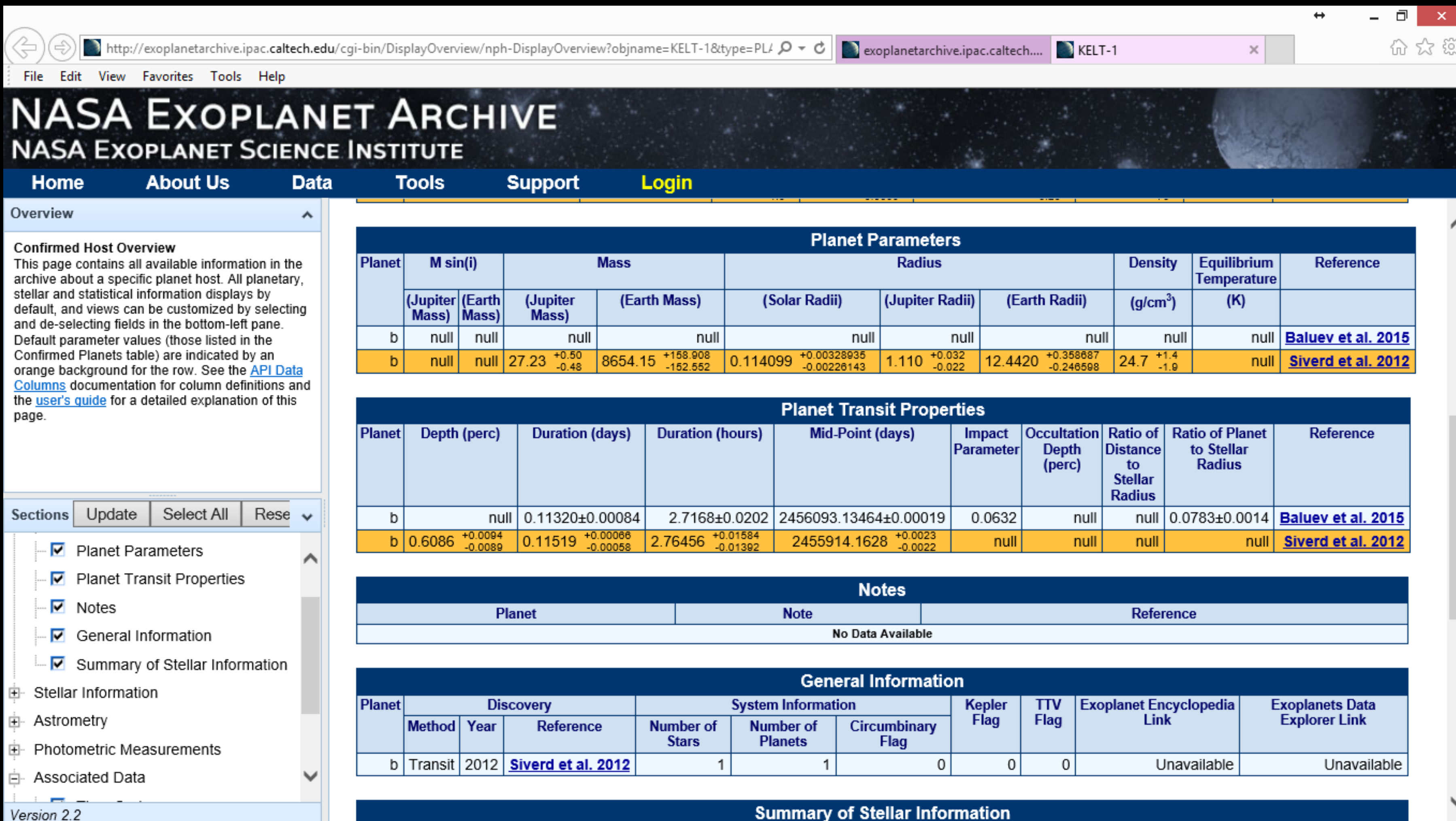
Planet Orbital Properties

Planet	Period (days)	Semi-Major Axis (AU)	Inclination (deg)	Eccentricity	Time of Periastron Passage (days)	Longitude of Periastron (deg)	Date of Orbital Solution	Reference
b	1.21749448±0.00000080	null	null	null	null	null	null	Baluev et al. 2015
b	1.217514±0.000015	0.02466±0.00016	$87.8^{+1.3}_{-1.9}$	$0.0099^{+0.010}_{-0.0069}$	$2455914.07^{+0.24}_{-0.26}$	61^{+71}_{-79}	null	Siverd et al. 2012

Planet Parameters

Planet	M sin(i)	Mass	Radius	Density	Equilibrium Temperature	Reference

Exoplanet Information (cont'd)



Planet Parameters

Planet	M sin(i)		Mass		Radius			Density	Equilibrium Temperature	Reference
	(Jupiter Mass)	(Earth Mass)	(Jupiter Mass)	(Earth Mass)	(Solar Radii)	(Jupiter Radii)	(Earth Radii)	(g/cm^3)	(K)	
b	null	null	null	null	null	null	null	null	null	Baluev et al. 2015
b	null	null	$27.23^{+0.50}_{-0.48}$	$8654.15^{+158.908}_{-152.552}$	$0.114099^{+0.00328935}_{-0.00226143}$	$1.110^{+0.032}_{-0.022}$	$12.4420^{+0.358687}_{-0.246598}$	$24.7^{+1.4}_{-1.9}$	null	Siverd et al. 2012

Planet Transit Properties

Planet	Depth (perc)	Duration (days)	Duration (hours)	Mid-Point (days)	Impact Parameter	Occultation Depth (perc)	Ratio of Distance to Stellar Radius	Ratio of Planet to Stellar Radius	Reference
b	null	0.11320±0.00084	2.7168±0.0202	2456093.13464±0.00019	0.0632	null	null	0.0783±0.0014	Baluev et al. 2015
b	$0.6086^{+0.0094}_{-0.0089}$	$0.11519^{+0.00066}_{-0.00058}$	$2.76456^{+0.01584}_{-0.01392}$	$2455914.1628^{+0.0023}_{-0.0022}$	null	null	null	null	Siverd et al. 2012

Notes

Planet	Note	Reference
No Data Available		

General Information

Planet	Discovery			System Information			Kepler Flag	TTV Flag	Exoplanet Encyclopedia Link	Exoplanets Data Explorer Link
	Method	Year	Reference	Number of Stars	Number of Planets	Circumbinary Flag				
b	Transit	2012	Siverd et al. 2012	1	1	0	0	0	Unavailable	Unavailable

Summary of Stellar Information

Exoplanet Information (cont'd)

http://exoplanetarchive.ipac.caltech.edu/cgi-bin/DisplayOverview/nph-DisplayOverview?objname=KELT-1&type=PL/

exoplanetarchive.ipac.caltech.... | KELT-1

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Confirmed Host Overview

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Sections | Update | Select All | Rese

- Planet Parameters
- Planet Transit Properties
- Notes
- General Information
- Summary of Stellar Information
- Stellar Information
- Astrometry
- Photometric Measurements
- Associated Data

http://exoplanetarchive.ipac.caltech.edu/index.html

	Method	Year	Reference	Number of Stars	Number of Planets	Circumbinary Flag	Flag	Flag	Link	Explorer Link
b	Transit	2012	Siverd et al. 2012	1	1	0	0	0	Unavailable	Unavailable

Summary of Stellar Information

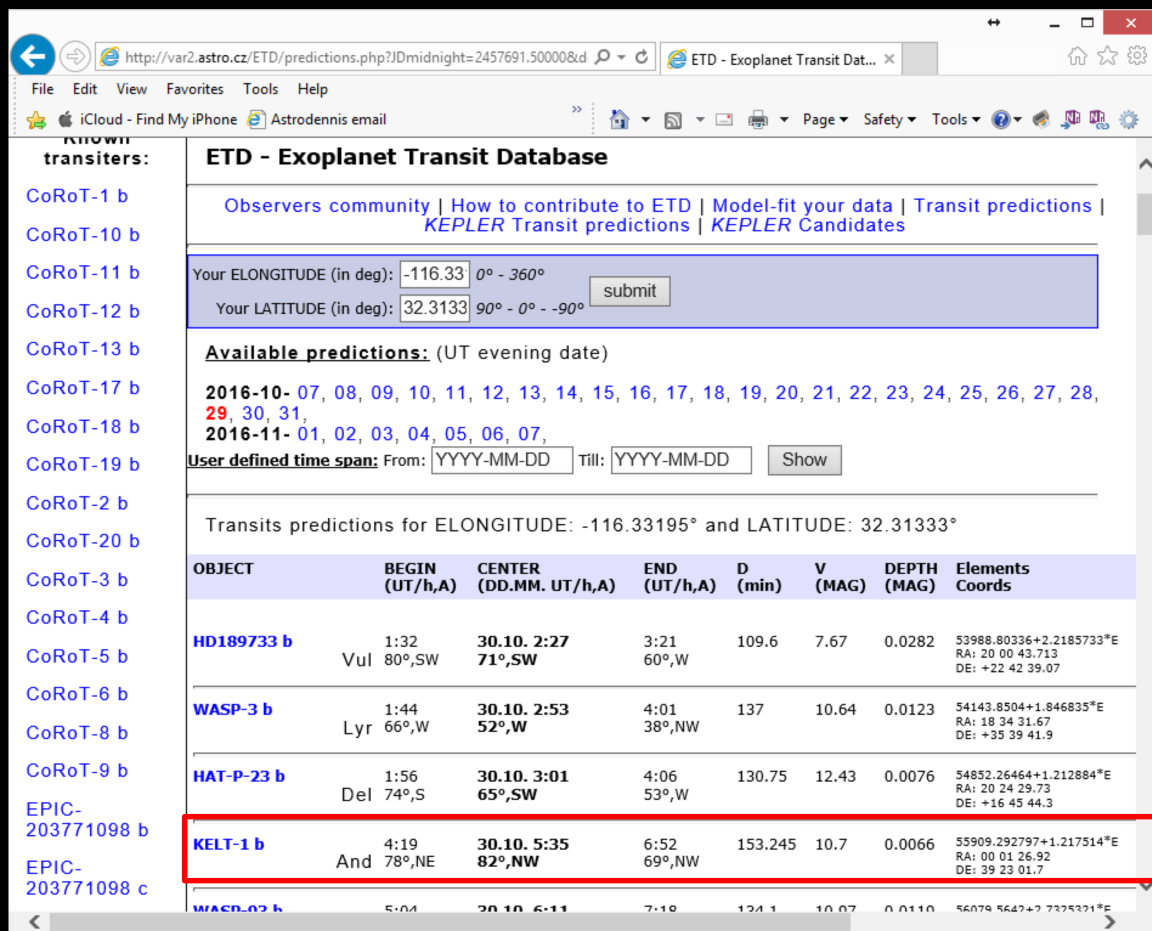
Right Ascension	00h01m26.91s	Declination	+39d23m01.7s
Galactic Longitude (deg)	112.50391	Galactic Latitude (deg)	-22.47352
Parallax (mas)	null	Distance (pc)	262±14
RA Proper Motion (mas/yr)	null	Dec Proper Motion (mas/yr)	null
Total Proper Motion (mas/yr)	null	Radial Velocity (km/s)	-14.2±0.2
B-band (mag)	11.363±0.065	K-band (mag)	9.437±0.019
Spectral Type	null	Effective Temperature (K)	6518±50
Surface Gravity ($\log_{10}$(cm/s^2))	null	Luminosity ($\log_{10}(L_{sun})$)	0.541579±0.0266225
Radius (R_{sun})	1.462±0.037	Mass (M_{sun})	1.324±0.026
Density (g/cm^3)	null	Age (Gyr)	null
Metallicity (dex)	null	Metallicity Ratio	null
V sin(i) (km/s)	56±2	S-index	null
log R'HK	null	X-ray activity, log(L_x)	null
Number of Hipparcos Light Curves	0	Number of Photometric non-Hipparcos Light Curves	0
Number of Radial Velocity Time Series	0	Number of Amateur Light Curves	0
Number of Spectra	0	Number of Images	3

Literature Time Series

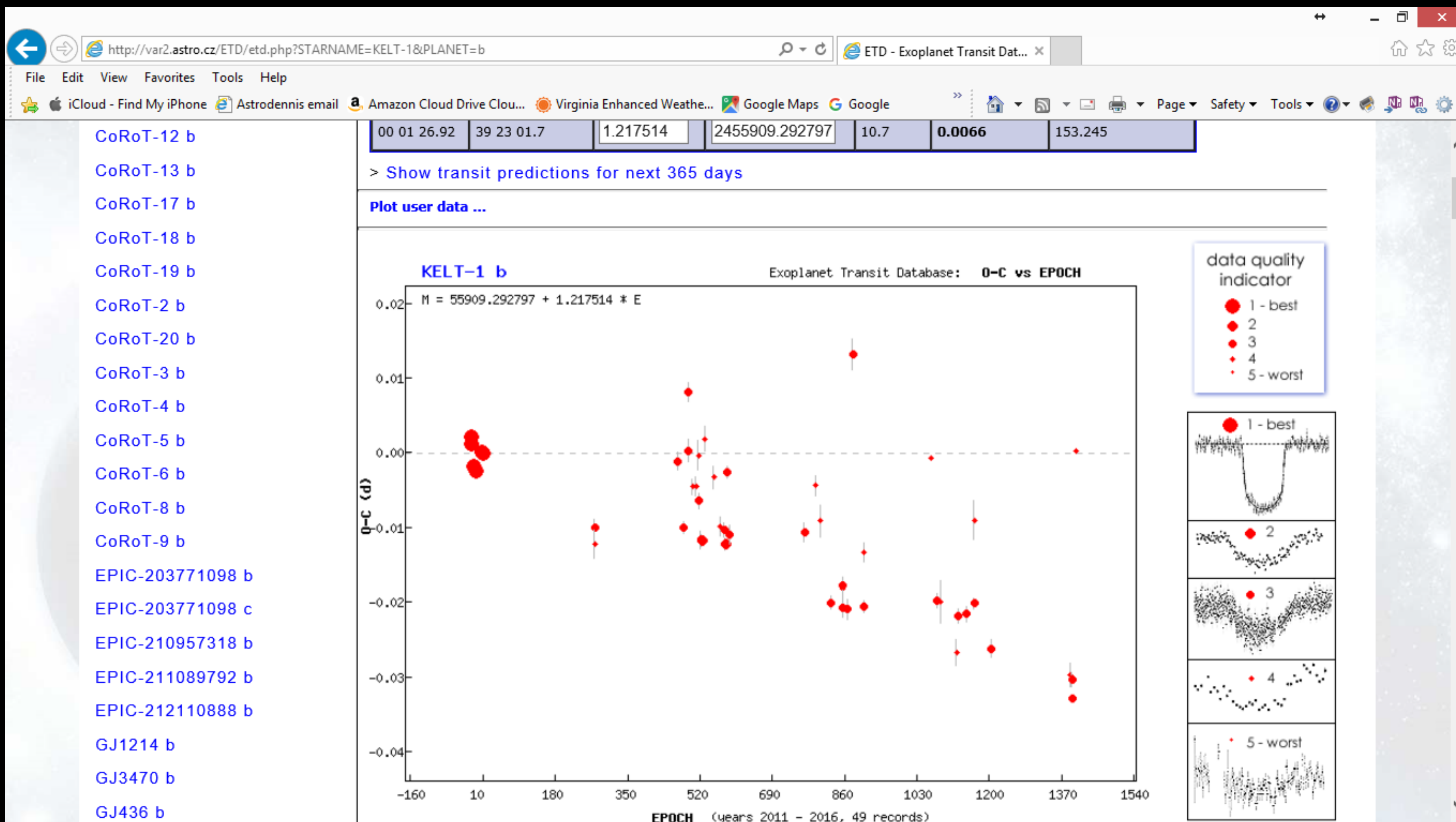
Type	Start Time	End Time	Number of Data Points	Wavelength	Method	Instrument/Telescope	File	Reference
No Data Available								

Exoplanet Information (cont'd)

- Exoplanet Transit Database (ETD) Website: http://var2.astro.cz/ETD/predictions.php



Exoplanet Information (cont'd)



Exoplanet Information (cont'd)

http://var2.astro.cz/ETD/predict_detail.php?delka=-116.33195&submit=submit&sirka=32.6133&STARNAME=KELT-1&

ETD - Exoplanet Transit Dat...

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GJ3470 b
GJ436 b
HAT-P-1 b
HAT-P-10/WASP-11 b
HAT-P-11 b
HAT-P-12 b
HAT-P-13 b
HAT-P-14 b
HAT-P-15 b
HAT-P-16 b
HAT-P-17 b
HAT-P-18 b
HAT-P-19 b
HAT-P-2 b
HAT-P-20 b
HAT-P-21 b
HAT-P-22 b
HAT-P-23 b
HAT-P-24 b
HAT-P-25 b
HAT-P-26 b
HAT-P-

15' x 15' image from the Digitized Sky Survey at the STScI Archive.

Your ELONGITUDE (in deg): -116.33 0° - 360°
Your LATITUDE (in deg): 32.6133 90° - 0° - -90°
submit

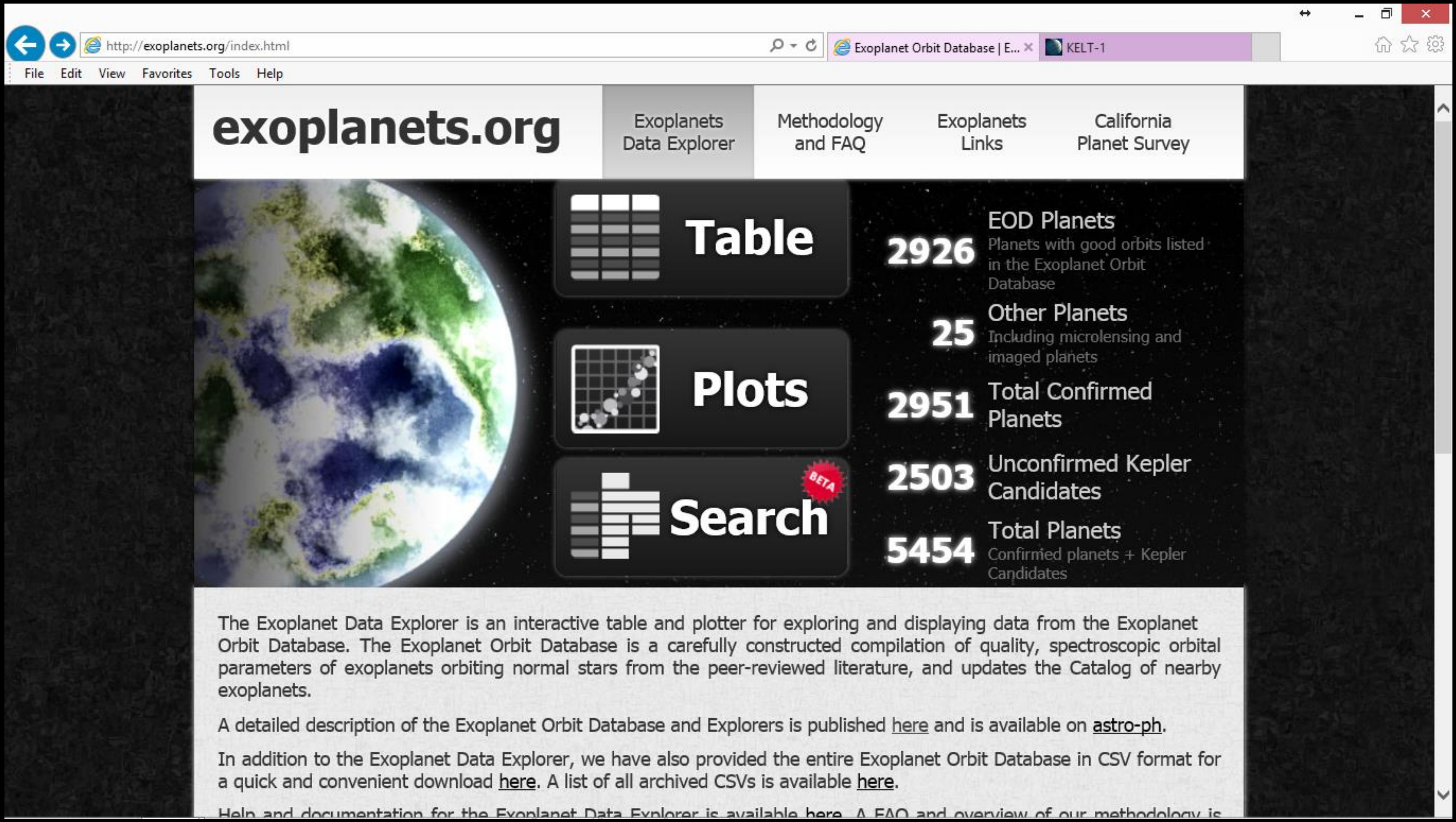
Transits predictions for NEXT 365 days.
ELONGITUDE: -116.33195° and LATITUDE: 32.6133°

Transit occurs below 20° in the sky. | During the daylight. | **Observable.**

Tmid (HJD)	BEGIN (UT/h,A)	CENTER (DD.MM. UT/h,A)	END (UT/h,A)
2457671.036	09.10 11:34 (31°,NW)	09.10. 12:51 (17°,NW)	09.10 14:07 (5°,NW)
2457672.253	10.10 16:47 (-14°,N)	10.10. 18:04 (-17°,N)	10.10 19:21 (-16°,N)
2457673.471	11.10 22:01 (-1°,NE)	11.10. 23:17 (10°,NE)	12.10 0:34 (22°,NE)
2457674.688	13.10 3:14 (53°,NE)	**13.10. 4:30 (68°,NE)**	13.10 5:47 (81°,NE)
2457675.906	14.10 8:27 (63°,NW)	**14.10. 9:44 (48°,NW)**	14.10 11:00 (34°,NW)
2457677.123	15.10 13:40 (5°,NW)	15.10. 14:57 (-5°,NW)	15.10 16:13 (-13°,N)
2457678.341	16.10 18:53 (-16°,N)	16.10. 20:10 (-11°,NE)	16.10 21:27 (-3°,NE)
2457679.558	18.10 0:07 (22°,NE)	18.10. 1:23 (36°,NE)	18.10 2:40 (50°,NE)
2457680.776	19.10 5:20 (81°,NE)	**19.10. 6:36 (80°,NW)**	19.10 7:53 (66°,NW)
2457681.993	20.10 10:33 (34°,NW)	**20.10. 11:50 (20°,NW)**	20.10 13:06 (7°,NW)
2457683.211	21.10 15:46 (-13°,N)	21.10. 17:03 (-17°,N)	21.10 18:20 (-17°,N)
2457684.428	22.10 20:59 (-4°,NE)	22.10. 22:16 (7°,NE)	22.10 23:33 (20°,NE)
2457685.646	24.10 2:13 (50°,NE)	**24.10. 3:29 (64°,NE)**	24.10 4:46 (79°,NE)
2457686.863	25.10 7:26 (66°,NW)	**25.10. 8:43 (51°,NW)**	25.10 9:59 (37°,NW)
2457688.081	26.10 12:39 (8°,NW)	26.10. 13:56 (-3°,NW)	26.10 15:12 (-12°,NW)
2457689.298	27.10 17:52 (-17°,N)	27.10. 19:09 (-13°,N)	27.10 20:26 (-5°,NE)
2457690.516	28.10 23:06 (19°,NE)	29.10. 0:22 (32°,NE)	29.10 1:39 (47°,NE)
2457691.733	30.10 4:19 (78°,NE)	**30.10. 5:35 (82°,NW)**	30.10 6:52 (69°,NW)
2457692.951	31.10 9:32 (38°,NW)	**31.10. 10:49 (23°,NW)**	31.10 12:05 (10°,NW)

Exoplanet Information (cont'd)

- http://exoplanets.org



Exoplanet Information (cont'd)

http://exoplanets.org/detail/KELT-2_A_b

Exoplanets Data Explor... | KELT-1 | Exoplanets Data Exp...

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Exoplanets Data Explorer Table Plots Send data reports to: datamaster@exoplanets.org and bug reports to: webmaster@exoplanets.org Help

KELT-2 A b

Velocity Profile Currently Unavailable

Discovery and References

Other Name	*Unavailable*
First Publication Date	2012
Method of discovery for the planet	Transit
Method of discovery of first planet in system	Transit
Orbit Reference	Beatty 2012
First Reference	Beatty 2012
EPE Link	KELT-2A
ETD Link	Kelt-2 b
Exoplanet Archive Link	KELT-2 A b

Orbital Parameters

Msin(i) [mjupiter]	1.520 ± 0.09
Planet Mass [mjupiter]	1.521 ± 0.09
Semi-Major Axis [au]	0.05497 ± 0.00092
Separation [au]	0.05497 ± 0.00092
Orbital Period [day]	$4.113791 +1\times10^{-5}/-9.9\times10^{-6}$
Velocity Semiamplitude [m/s]	161.1 +7.8/-7.9
Orbital Eccentricity	0
Orbit Inclination [deg]	88.6 +1/-1.4
Argument of Periastron [deg]	90
BigΩ [deg]	*Unavailable*
Time of Periastron [jd]	2455974.60335 +0.00082/-0.00083
Velocity Slope [m/s/day]	0.63 ± 0.24
Spin-Orbit Misalignment [deg]	*Unavailable*
Transit	✓

Stellar Properties

Star Name	KELT-2 A
Binary Flag	✓
Mass of Star [msun]	1.308 +0.028/-0.025
Radius of Star [rsun]	1.828 +0.07/-0.034
[Fe/H]	-0.018 ± 0.069
T_{eff} [k]	6151 +49/-50
Density of star [g/cm^3]	*Unavailable*
$\log_{10}(g)$	4.030 +0.013/-0.028
Vsin(i) [km/s]	9.0 ± 2
Gamma [km/s]	*Unavailable*

Stellar Magnitudes

V mag	8.7
B-V	0.52
2MASS J	7.7
2MASS H	7.4
2MASS K_S	7.3
S_{HK}	*Unavailable*
log R_{HK}	*Unavailable*
KP	*Unavailable*

Coordinates and Catalogs

Predicting Transit Times
Example: Kelt-1

From Discovery Paper (Siverd et al. 2012):

TABLE 4
MEDIAN VALUES AND 68% CONFIDENCE INTERVALS FOR THE PHYSICAL AND ORBITAL PARAMETERS OF THE KELT-1 SYSTEM

Variable	Description (Units)	Value ($e \neq 0$)	Value ($e \equiv 0$)
Stellar Parameters:			
M_*	Mass ($M_\odot$)	1.324 ± 0.026	$1.322^{+0.026}_{-0.025}$
R_*	Radius ($R_\odot$)	$1.462^{+0.037}_{-0.024}$	$1.452^{+0.033}_{-0.019}$
L_*	Luminosity ($L_\odot$)	$3.48^{+0.22}_{-0.18}$	$3.43^{+0.20}_{-0.16}$
ρ_*	Density (cgs)	$0.597^{+0.026}_{-0.039}$	$0.610^{+0.018}_{-0.037}$
$\log g$	Surface gravity (cgs)	$4.229^{+0.012}_{-0.019}$	$4.2351^{+0.0087}_{-0.017}$
$T_{\rm eff}$	Effective temperature (K)	6518 ± 50	6517 ± 49
[Fe/H]	Metallicity	0.008 ± 0.073	0.009 ± 0.073
$v \sin I_*$	Rotational velocity (m s^{-1})	56000 ± 2000	56000 ± 2000
λ	Spin-orbit alignment (degrees)	2 ± 16	1 ± 15
Planetary Parameters:			
e	Eccentricity	$0.0099^{+0.010}_{-0.0069}$	—
ω_*	Argument of periastron (degrees)	61^{+71}_{-79}	—
P	Period (days)	1.217514 ± 0.000015	1.217513 ± 0.000015
a	Semi-major axis (AU)	0.02466 ± 0.00016	0.02464 ± 0.00016
M_P	Mass (M_J)	$27.23^{+0.50}_{-0.48}$	$27.24^{+0.49}_{-0.48}$
R_P	Radius (R_J)	$1.110^{+0.032}_{-0.022}$	$1.102^{+0.030}_{-0.018}$
ρ_P	Density (cgs)	$24.7^{+1.4}_{-1.9}$	$25.2^{+1.2}_{-1.8}$
$\log g_P$	Surface gravity	$4.738^{+0.017}_{-0.023}$	$4.744^{+0.013}_{-0.021}$
T_{eq}	Equilibrium temperature (K)	2422^{+32}_{-26}	2414^{+29}_{-23}
Θ	Safronov number	$0.912^{+0.023}_{-0.028}$	$0.919^{+0.019}_{-0.024}$
$\langle F \rangle$	Incident flux (10^9 erg s^{-1} cm^{-2})	$7.81^{+0.42}_{-0.33}$	$7.71^{+0.38}_{-0.29}$

TABLE 5
MEDIAN VALUES AND 68% CONFIDENCE INTERVALS FOR THE LIGHCURVE AND RADIAL VELOCITY PARAMETERS OF THE KELT-1 SYSTEM

Parameter	Description (Units)	Value
RV Parameters:		
T_C	Time of inferior conjunction ($\rm BJD_{TDB}$)	$2455914.1628^{+0.0023}_{-0.0022}$
T_P	Time of periastron ($\rm BJD_{TDB}$)	$2455914.07^{+0.24}_{-0.26}$
K	RV semi-amplitude (m s^{-1})	4239 ± 52
K_R	RM amplitude (m s^{-1})	342 ± 13
$M_P \sin i$	Minimum mass (M_J)	$27.20^{+0.49}_{-0.48}$
M_P/M_*	Mass ratio	0.01964 ± 0.00028
u	RM linear limb darkening	$0.5842^{+0.0044}_{-0.0039}$
γ_0	zero point for Orbital RVs (Table 7) (m s^{-1})	-14200 ± 50 (stat.)± 200 (sys.)
γ_1	zero point for RM RVs (Table 8) (m s^{-1})	-14200^{+56}_{-59} (stat.)± 200 (sys.)
$e \cos \omega_*$		$0.0018^{+0.0092}_{-0.0059}$
$e \sin \omega_*$		$0.0041^{+0.011}_{-0.0062}$
$f(m1, m2)$	Mass function (M_J)	$0.01006^{+0.00038}_{-0.00037}$
Primary Transit Parameters:		
R_P/R_*	Radius of the planet in stellar radii	$0.07801^{+0.00060}_{-0.00058}$
a/R_*	Semi-major axis in stellar radii	$3.626^{+0.052}_{-0.080}$
i	Inclination (degrees)	$87.8^{+1.3}_{-1.9}$
b	Impact parameter	$0.141^{+0.11}_{-0.082}$
δ	Transit depth	$0.006086^{+0.000094}_{-0.000089}$
T_{FWHM}	FWHM duration (days)	0.10642 ± 0.00045
τ	Ingress/egress duration (days)	$0.00870^{+0.00044}_{-0.00018}$
T_{14}	Total duration (days)	$0.11519^{+0.00066}_{-0.00058}$
P_T	A priori non-grazing transit probability	$0.2558^{+0.0074}_{-0.0052}$
$P_{T,G}$	A priori transit probability	$0.2991^{+0.0088}_{-0.0061}$
$T_{C,0}$	transit time for PvdKO UT 2011-12-03 ($\rm BJD_{TDB}$)	2455899.5550 ± 0.0010

Predicting Transit Times (cont'd)

- Predictions:

  Current T_c = Period* Phase + Epoch T_c
  Begin transit time = T_c – Duration/2
  End transit time = T_c + Duration/2

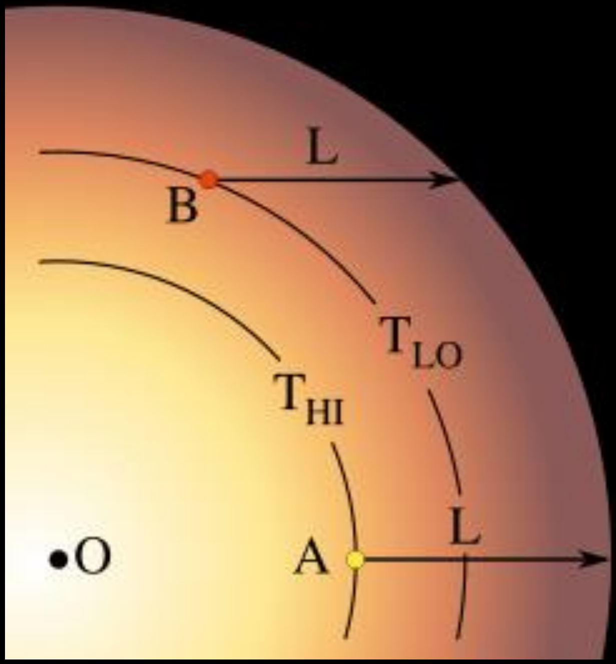
KELT-1 Predicted Transit Times

		Duration			
Source	Days	Minutes	Epoch (BJD-TDB)	Period
NASA	0.11519	165.874	2455914.16280	1.217514
ETD	0.10642	153.245	2455909.29280	1.217514
KELT	0.11500	165.6	2456863.80977	1.217494

Source	Phase	Calculated Tc		Shown
NASA	1460	2457691.73324	10/30/16 5:35	Same
ETD	1464	2457691.73329	10/30/16 5:35	Same
KELT	680	2457691.70569	10/30/16 4:56	Same !

Source		Calculated Ingress/Egress Times		Shown
NASA:	Ingress time:	2457691.67565	10/30/16 4:12	10/30/16 3:37
	Egress time:	2457691.79084	10/30/16 6:58	10/30/16 7:34
ETD	Ingress time:	2457691.68008	10/30/16 4:19	Same
	Egress time:	2457691.78650	10/30/16 6:52	Same
KELT	Ingress time:	2457691.64819	10/30/16 3:33	Same
	Egress time:	2457691.76319	10/30/16 6:19	Same

Limb Darkening



= a function of:

filter used

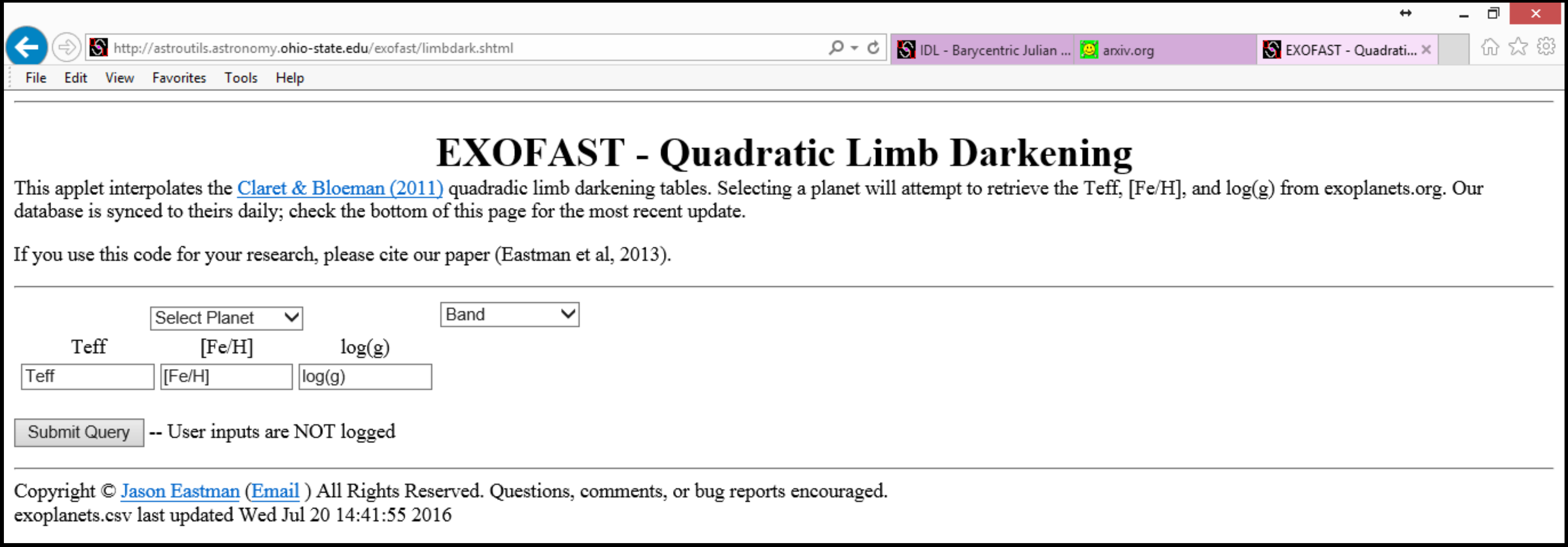
star's temperature - T_{eff}

star's metallicity - Fe/H

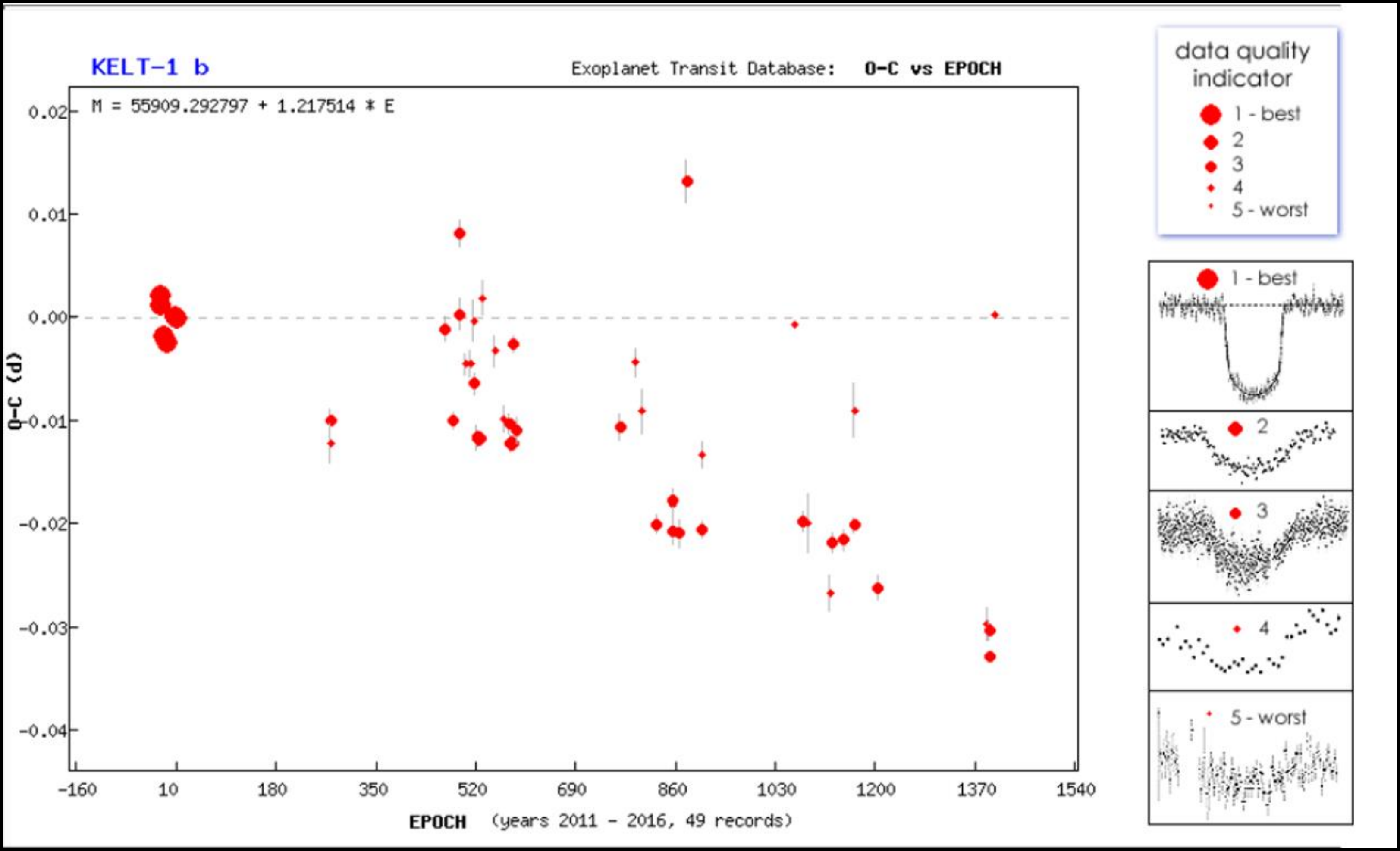
star's surface gravity - log(g)

Limb Darkening Coefficients

- Ohio State Site: http://astroutils.astronomy.ohio-state.edu/exofast/limbdark.shtml



Effects of a Period Off by 1.7 Seconds!



Phases

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

The Worksheet

		Exoplanet:	KELT-1b		
		Observer:	Dennis Conti		
Item	Host Star/Exoplanet Information:	(click here)			
1	RA:	00:01:26.92			
2	Dec:	+39:23:01.7			
3	Period (days):	1.275007			
4	R_*:	1.462			
5	T_{eff} :	6518			
6	V mag:	10.7			
	Suggested range of comp stars:	10.26 to 11.45 mag			
7	Link to Reference Paper (optional):	https://arxiv.org/pdf/1206.1635v1.pdf			
8	Date of Observation (UT):	10/12/2016			
			BJD_TDB		
			(click here)		
9	Ingress:		2457674.60300		
10	Egress:		2457674.71800		
	Predicted midpoint:		2457674.66050		
11	Model fit midpoint (T_c):		2457674.65689		
		Delta:	5.20	minutes	
	Observing Location:				
12	Latitude:		38:55:48.51 N		
13	Longitude:		76:29:17.78 W		
14	Elevation (m):		0		
15	Aperture (mm):		280		
16	Focal length (mm):		3327		
17	Make/model of CCD Camera:		SX694M		
18	Gain (e-/ADU):		0.3		
19	Readout noise (e-):		5		
20	Dark current (e-/pixel/sec):		0.003		
21	Point of where CCD goes non-linear (ADUs):		45000		
		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):	5			
26	Filter used:	V			
	Limb darkening coefficients:	(click here)			
27	Quadratic LD u1:	0.3486438	Coeff'.s used:		
28	Quadratic LD u2:	0.3152568	Teff=6518,Fe/H=0.008,log(g)=4.229		
	Image scale (arcsec/pixel):	0.56	0.56		
	FOV (arcmin):	12.90	10.32		
29	FWHM (arcseconds):	1.89			
	FWHM (pixels):	3.36			
	Initial Settings:				
30	FWHM pixel multiplier:				
	Aperture radius:				
31	Inner annulus radius:				
	Outer annulus radius:				
	Final Settings:				
32	Aperture radius:	6	Segments:		
33	Inner annulus radius:	11	1-1212		
34	Outer annulus radius:	17	1226-1808		
		# of Science Images:			
35	Original #:	1972	Final #:	1800	
36	Images not used:	1210,1214-1220,1809-1972			

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: Analysis Files, 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)

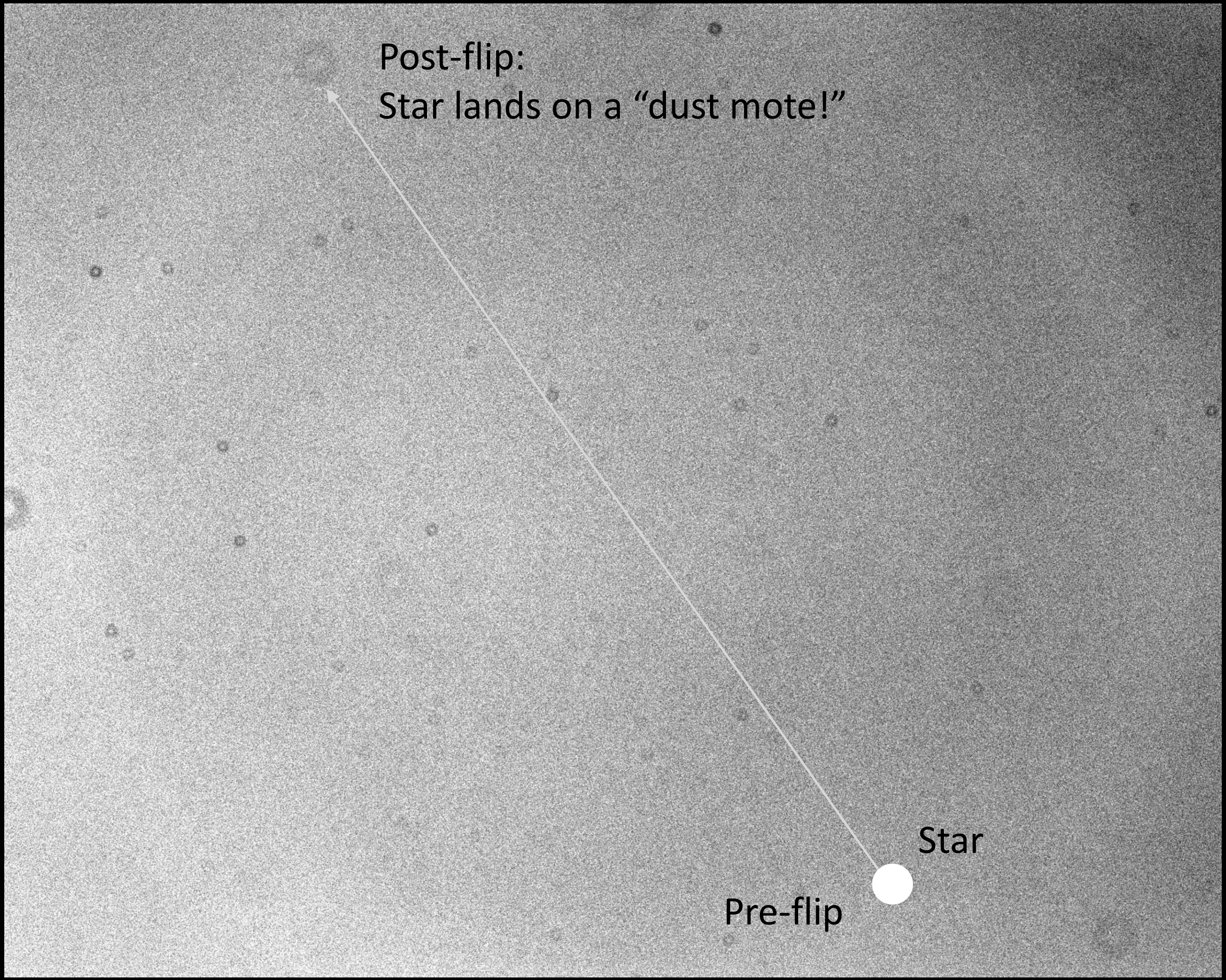
Image Capture Phase

- 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

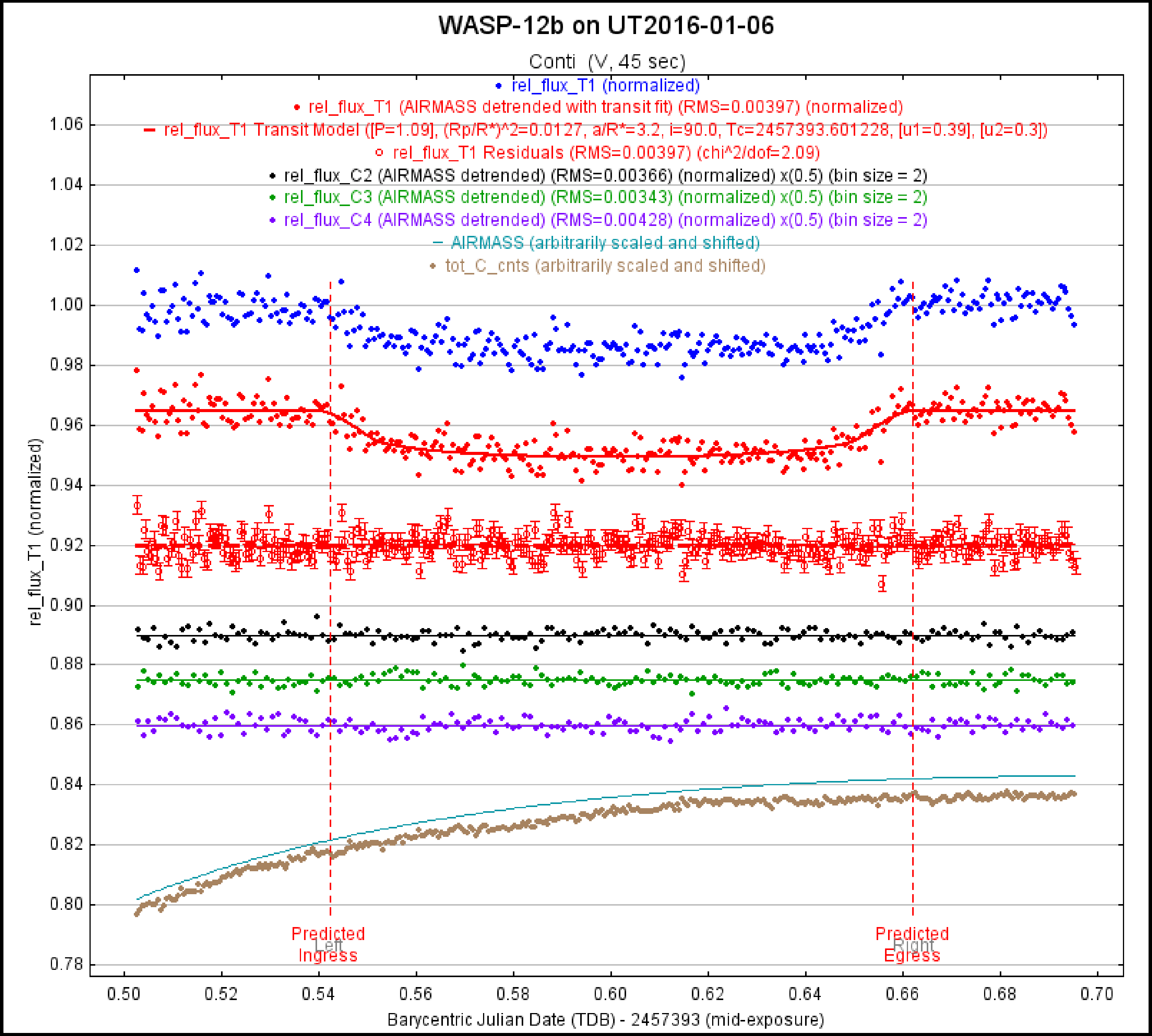


Post-Processing and Modelling

- 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
- Conduct differential photometry on calibrated files

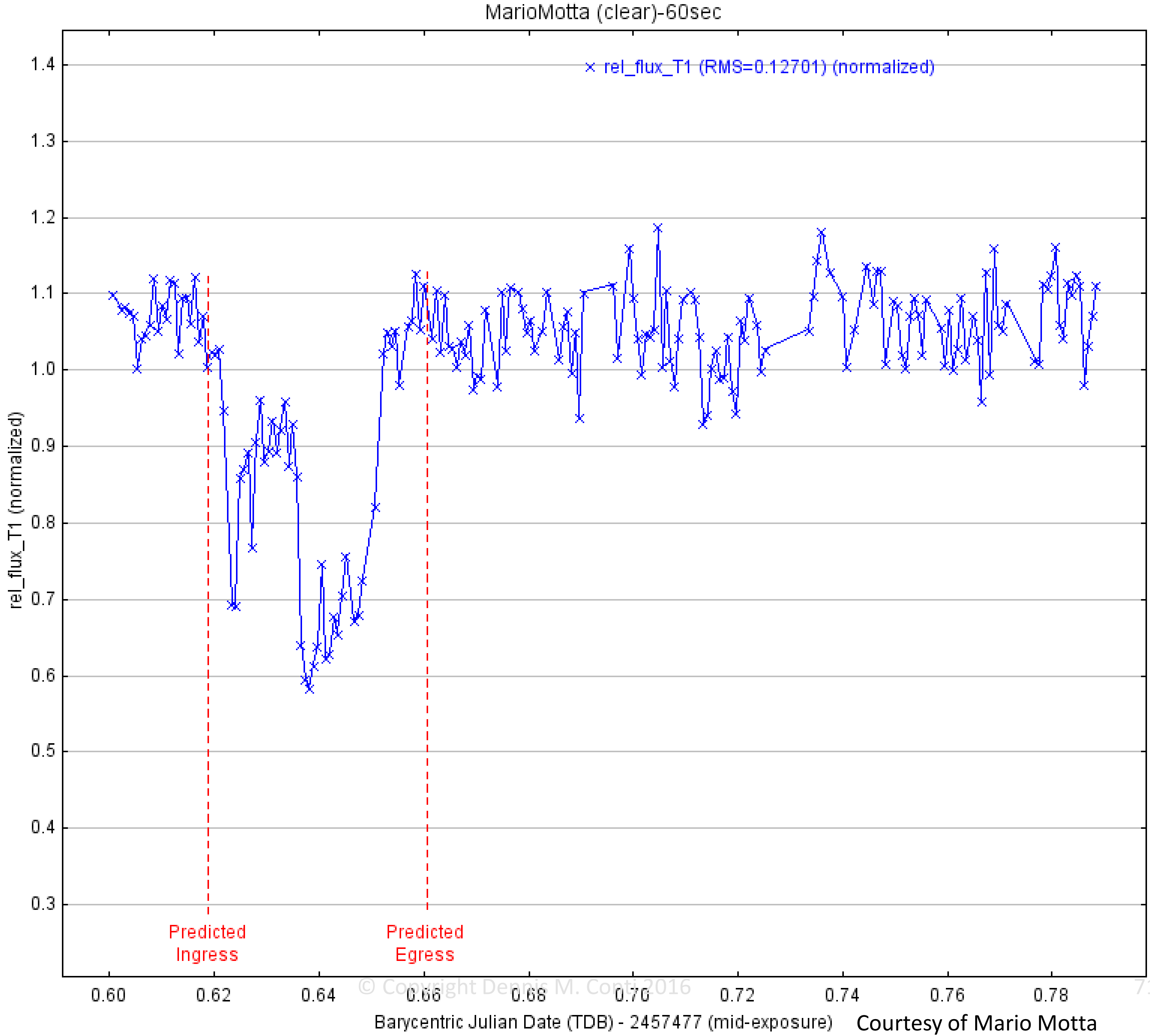
Conduct Model Fit

- 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



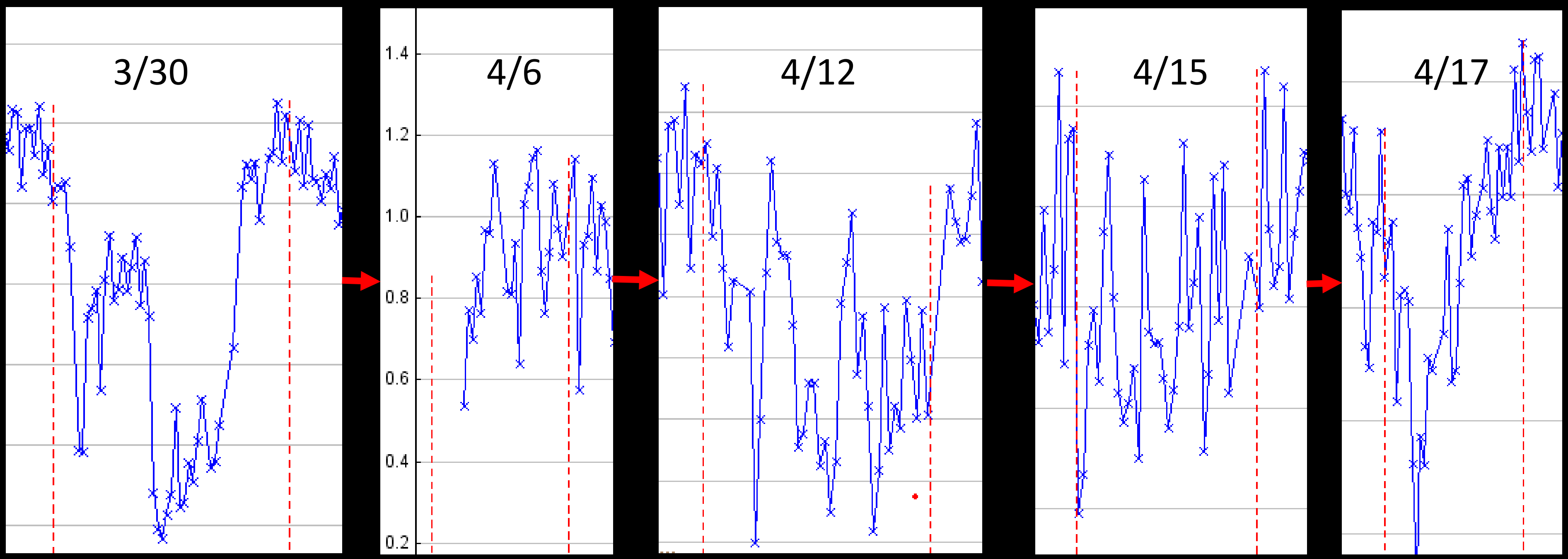
WASP-12b on UT2016-01-06
Conti (V, 45 sec)
rel_flux_T1 (normalized)
rel_flux_T1 (AIRMASS detrended with transit fit) (RMS=0.00397) (normalized)
rel_flux_T1 Transit Model ([P=1.09], (Rp/R*)^2=0.0127, a/R*=3.2, i=90.0, Tc=2457393.601228, [u1=0.39], [u2=0.3])
rel_flux_T1 Residuals (RMS=0.00397) (chi^2/dof=2.09)
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)

A Disintegrating Planetesimal: WD1145 UT2016-03-30



Courtesy of Mario Motta

WD-1145+017 Observations



Courtesy of Mario Motta

Tonight's Observation:
KELT-1

KELT-1b

- Discovery paper: Siverd, et al., 2012
  "KELT-1b: A Strongly Irradiated, Highly inflated, Short Period, 27 Jupiter-Mass Companion Transiting a Mid-F Star"

- Not yet officially designated as an "exoplanet"

- Stellar parameters:
  - R_*=1.462
  - V Magnitude = 10.7
  - Teff = 6518
  - Fe/H = 0.008
  - Log(g) = 4.229

Worksheet

		Exoplanet:	KELT-1b		
		Observer:			
<u>Item</u>	Host Star/Exoplanet Information:	(click here)			
1	RA:	00:01:26.92			
2	Dec:	+39:23:01.7			
3	Period (days):	1.275007			
4	R_*:	1.462			
5	T_{eff}:	6518			
6	V mag:	10.7			
	Suggested range of comp stars:	10.26 to 11.45 mag			
7	Link to Reference Paper (optional):	https://arxiv.org/pdf/1206.1635v1.pdf			
8	Date of Observation (UT):	10/30/2016			
			BJD_TDB		
			(click here)		
9	Ingress:		2457691.64819		
10	Egress:		2457691.76319		
	Predicted midpoint:		2457691.70569		
11	Model fit midpoint (T_c):				
		Delta:	#VALUE!	minutes	
	Observing Location:				
12	Latitude:		32:36:48N		
13	Longitude:		116:19:55W		
14	Elevation (m):		1131		
15	Aperture (mm):				
16	Focal length (mm):				
17	Make/model of CCD Camera:				
18	Gain (e-/ADU):				
19	Readout noise (e-):				
20	Dark current (e-/pixel/sec):				
21	Point of where CCD goes non-linear (ADUs):				
		<u>X</u>	<u>Y</u>		
22	No. of pixels (unbinned):				
23	Pixel size (microns -unbinned):				
24	Binning used for this observation:				
25	Exposure time (secs):				
26	Filter used:				
	Limb darkening coefficients:	(click here)			
27	Quadratic LD u1:		Coeff'.s used:		
28	Quadratic LD u2:		Teff=6518,Fe/H=0.008,log(g)=4.229		
	Image scale (arcsec/pixel):	#VALUE!	#VALUE!		
	FOV (arcmin):	#VALUE!	#VALUE!		
29	FWHM (arcseconds):	#VALUE!			
	FWHM (pixels):				
	Initial Settings:				
30	FWHM pixel multiplier:				
	Aperture radius:				
31	Inner annulus radius:				
	Outer annulus radius:				
	Final Settings:				
32	Aperture radius:				
33	Inner annulus radius:				
34	Outer annulus radius:				
		# of Science Images:			
35	Original #:		Final #:		
36	Images <u>not</u> used:				

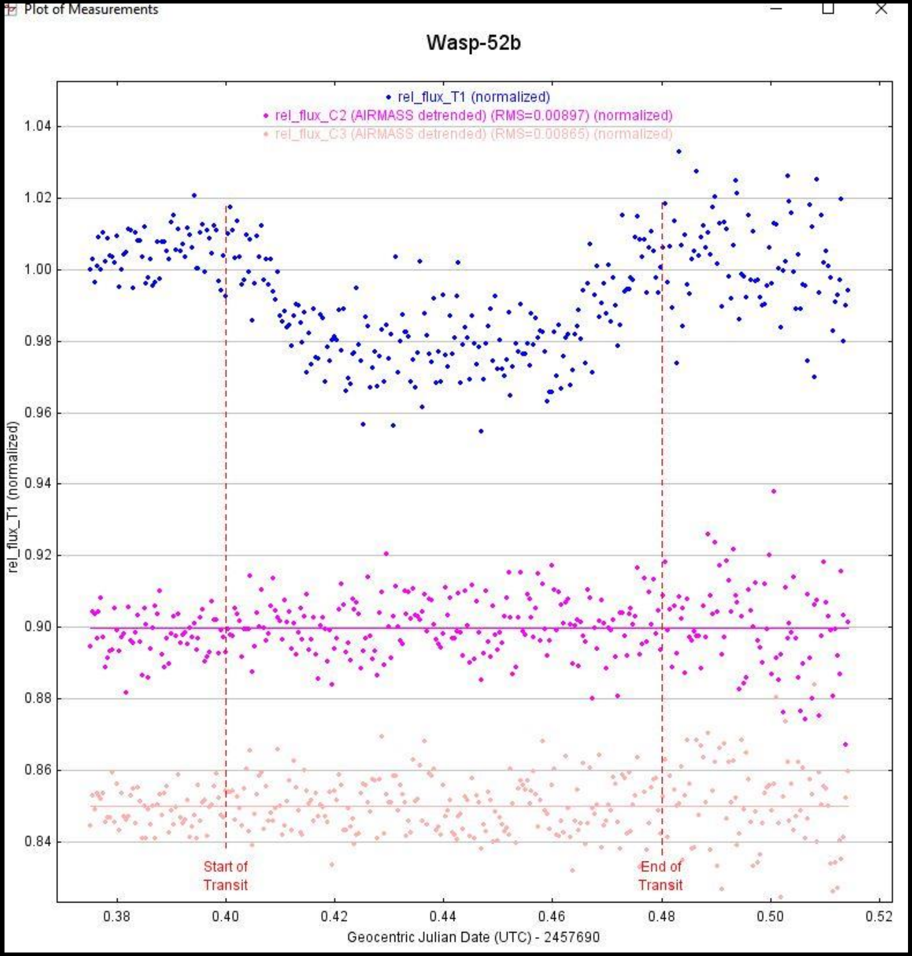
AstroImageJ

- Freeware downloadable from: http://www.astro.louisville.edu/software/astroimagej/
- See "A Practical Guide to Exoplanet Observing" for a step-by-step tutorial on using it: http://astrodennis.com
- Analysis of last night's observation

Recap from Day 1

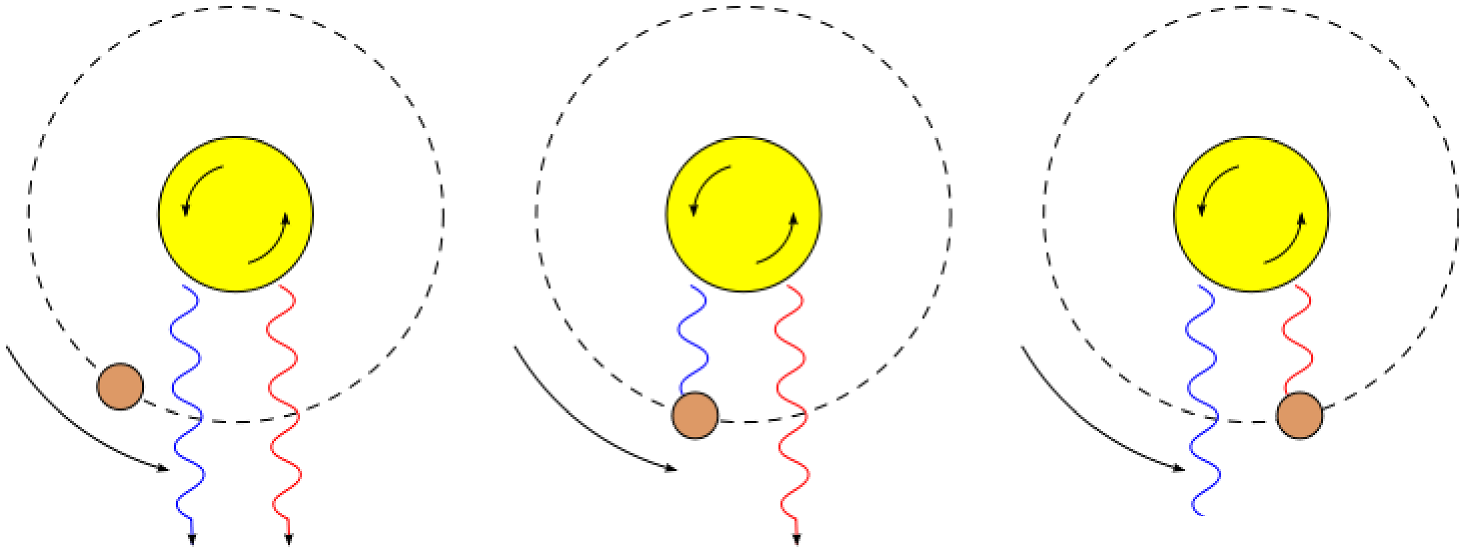
Definition of “Small Telescope”

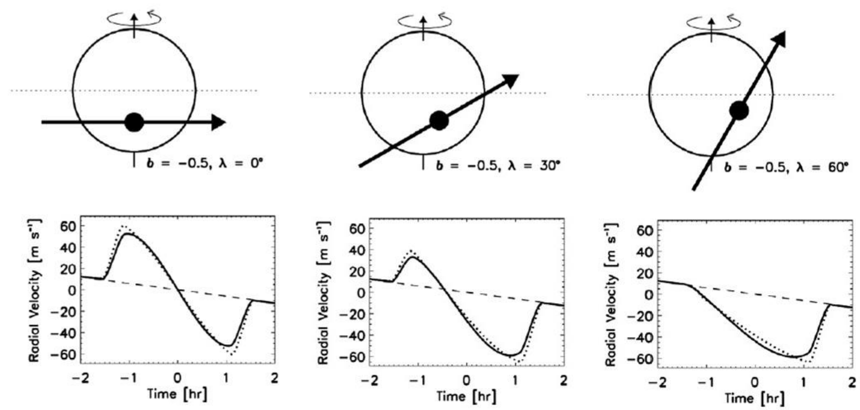
Now redefined to be 6” in aperture or greater!



Courtesy of Mark Trapnell

The Rossiter-McLaughlin Effect





"Highly Inflated" Jupiters

- See:
  http://www.cfa.harvard.edu/news/201241

What time is it?

Time base = reference location and time standard (clock)

- Local time at San Diego, CA: 13:00 on October 29, 2016
- UTC time at Greenwich, England: 20:00 on October 29, 2016
- JD (above in Julian Date form): 2457691.33333

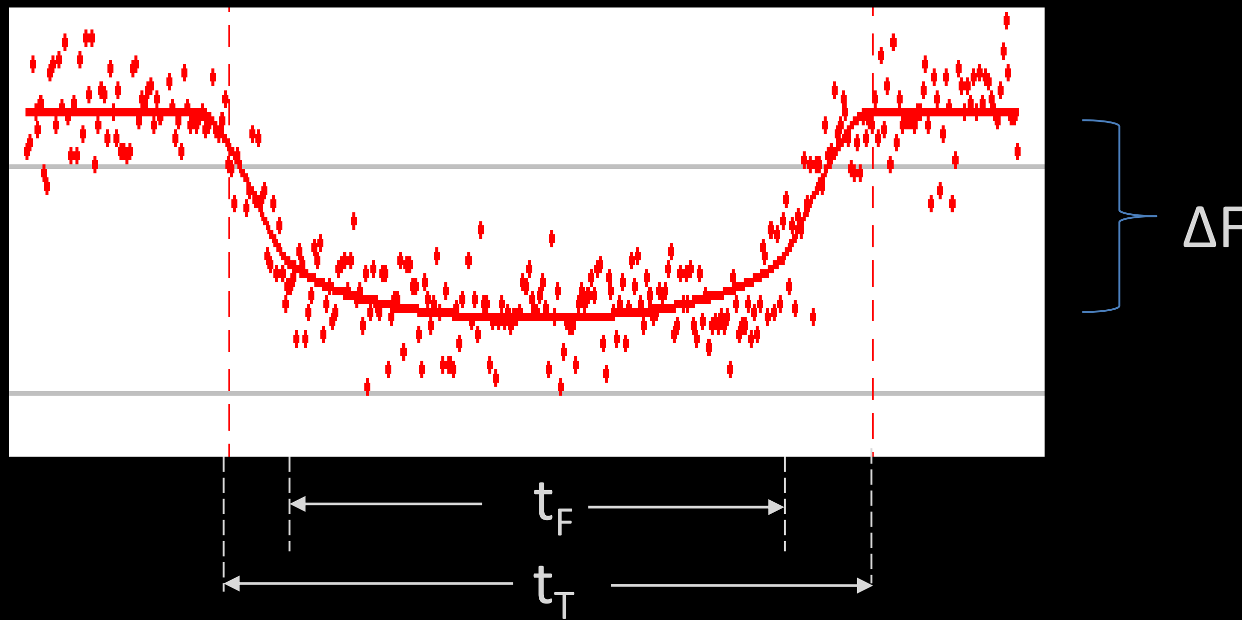
  ↓ +6.4 min.

- HJD_{UTC} (Heliocentric Julian Date, UTC) 2457691.33780
  for Kelt-1 at (00h 01m 26.92s, 39°23'01.7")

  ↓ +1.1 min.

- BJD_{TDB} (Barycentric Julian Date, 2457691.33858
  Barycentric Dynamical Time) for Kelt-1
  and 32:36:48N, 116:19:55W, 1131m alt.

Exoplanet Properties from Primary Eclipse



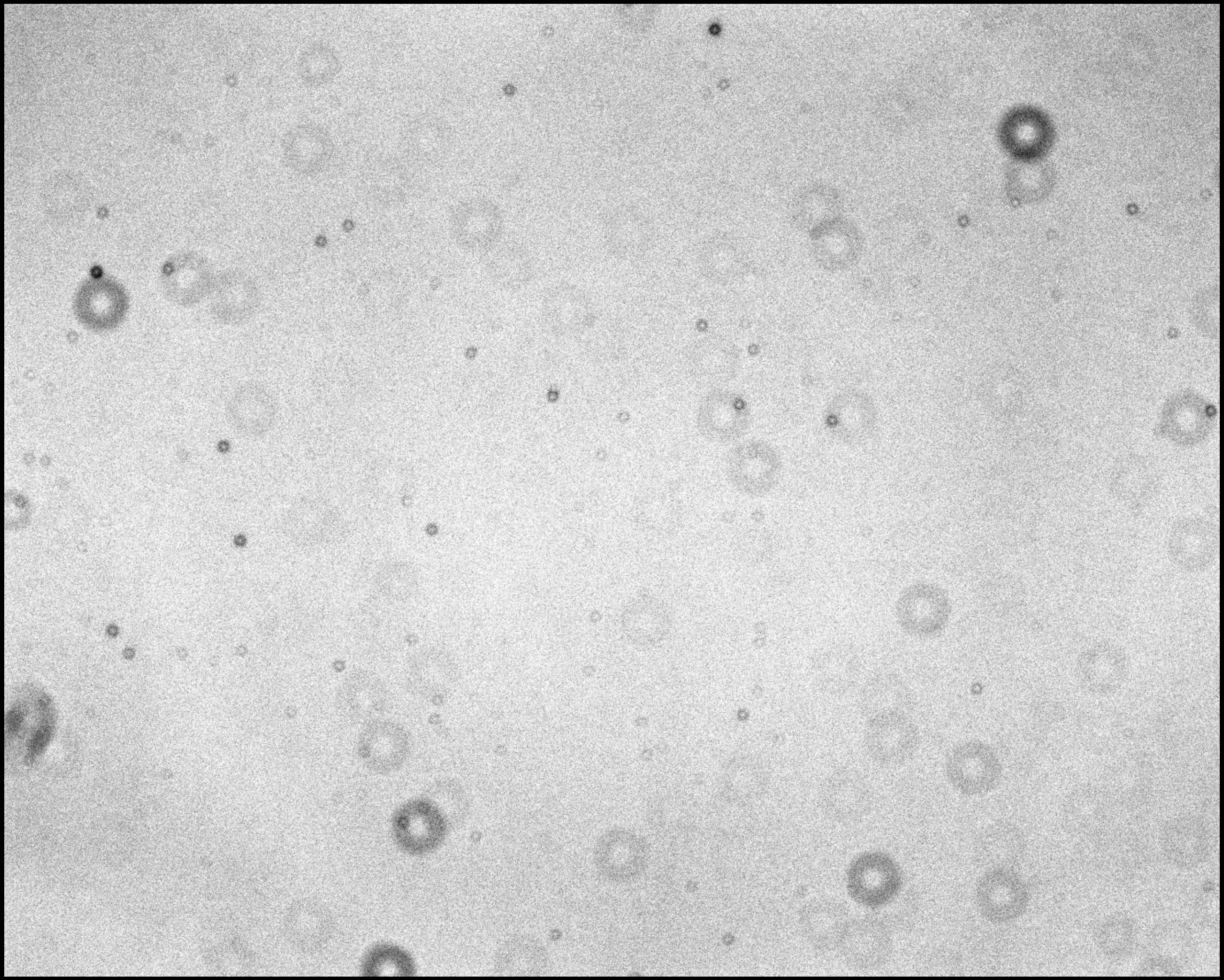
- Exoplanet radius: $R_p = f_1(R_*,\ \Delta F)$
- Exoplanet orbit : $a/R_* = f_2(P, \Delta F, t_T, t_F)$
- Exoplanet orbit inclination: $i = f_3(P, \Delta F, t_T, t_F)$

(see Seager, et al. 2002)

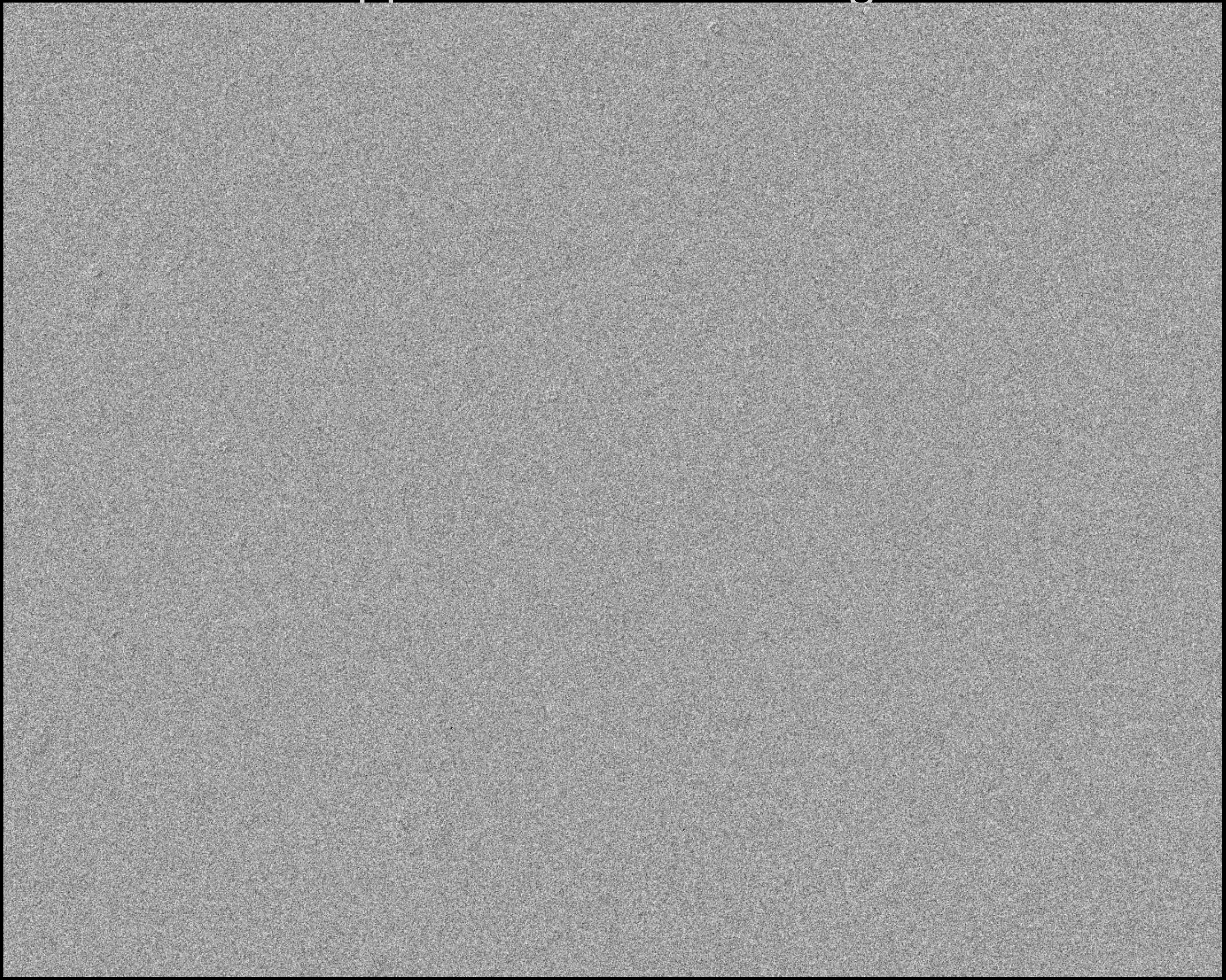
Testing Master Flat

- Create a Master Flat from raw flat images
- Apply the Master Flat to one of the raw flat images
- Evaluate the resulting calibrated image for any signs of dust motes, etc.

Example Raw Flat Image



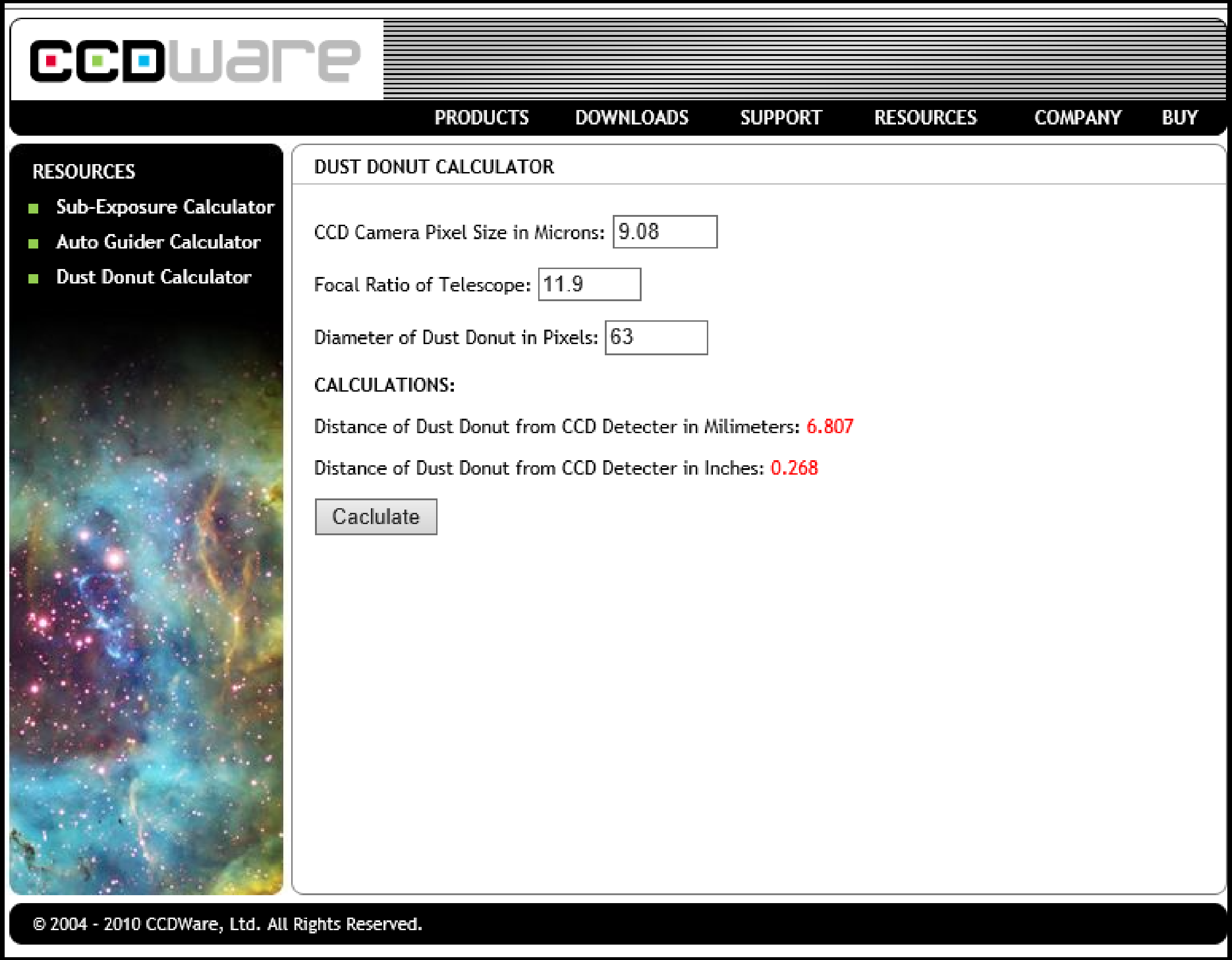
Master Flat Created by Nebulosity and Applied to Raw Flat Image



Master Flat Created by AIJ and Applied to Raw Flat Image

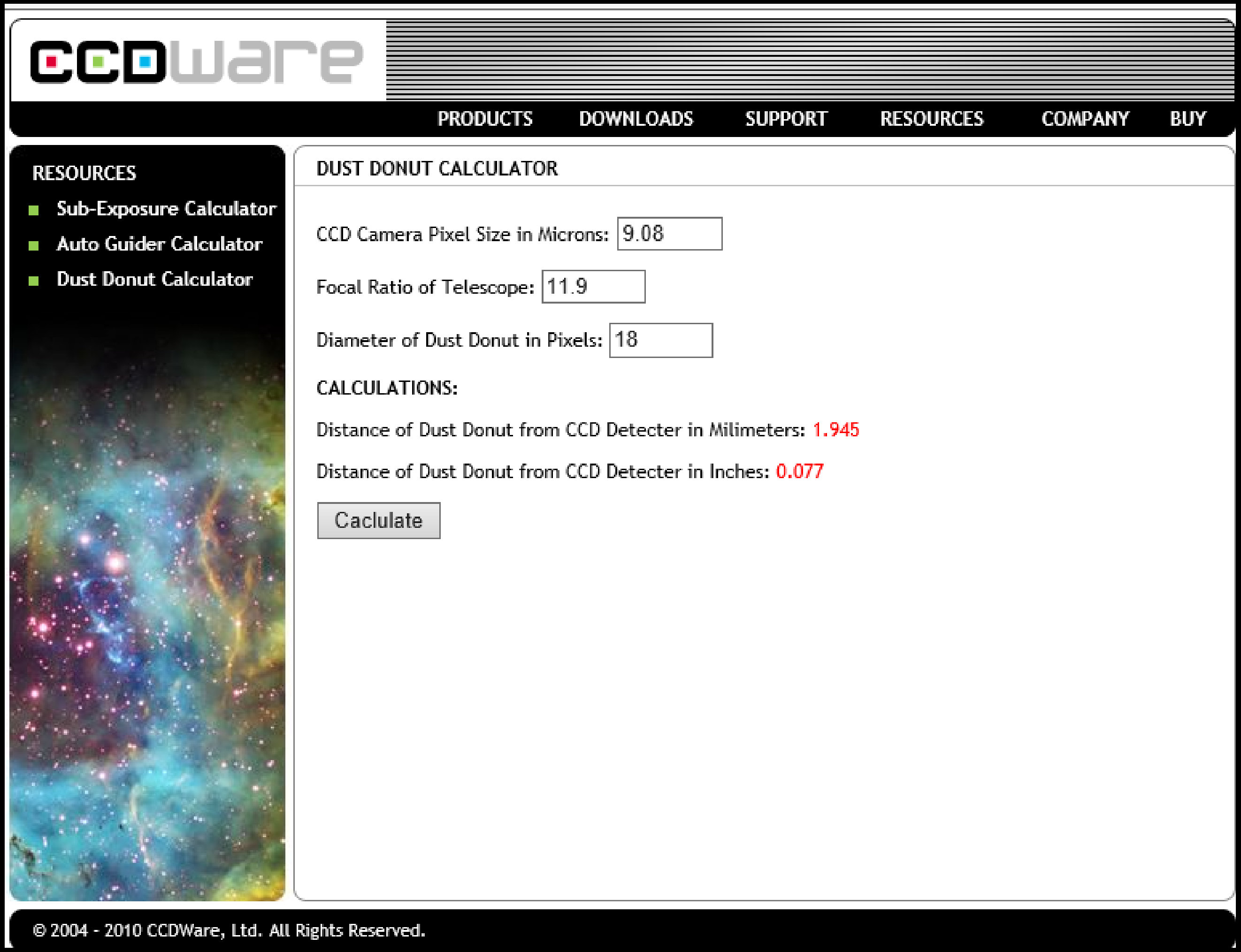
Dust Donut Calculator:

http://www.ccdware.com/resources/dust.cfm



Dust Donut Calculator:

http://www.ccdware.com/resources/dust.cfm



Conduct AIJ Analysis of KELT-1b Observation

- Follow AIJ Pipeline in Addendum

Outline of Observation Paper

Abstract

1. Introduction – include: what's unique about this target and summarize discovery paper

2. Observation
   - 2.1 Instrumentation – describe observatory and instrumentation

   - 2.2 Observing Conditions
     - 2.2.1 Possible Systematics
     - 2.2.2 Weather Conditions

   - 2.3 Workflow
     - 2.3.1 Calibration: describe methods for generating bias, darks, flats
     - 2.3.2 Comparison star selection
     - 2.3.3 Selection of priors:
       - Period
       - Star radius
       - Limb-darkening coefficients
     - 2.3.4 Normalization region used

3. Observation Results
   - 3.1 Pixel-to-Pixel movement
   - 3.2 Model optimization process
   - 3.3 Model results: R_p/R_*, a/R_*, T_c, RMS

4. Comparison to Published Data

5. Summary

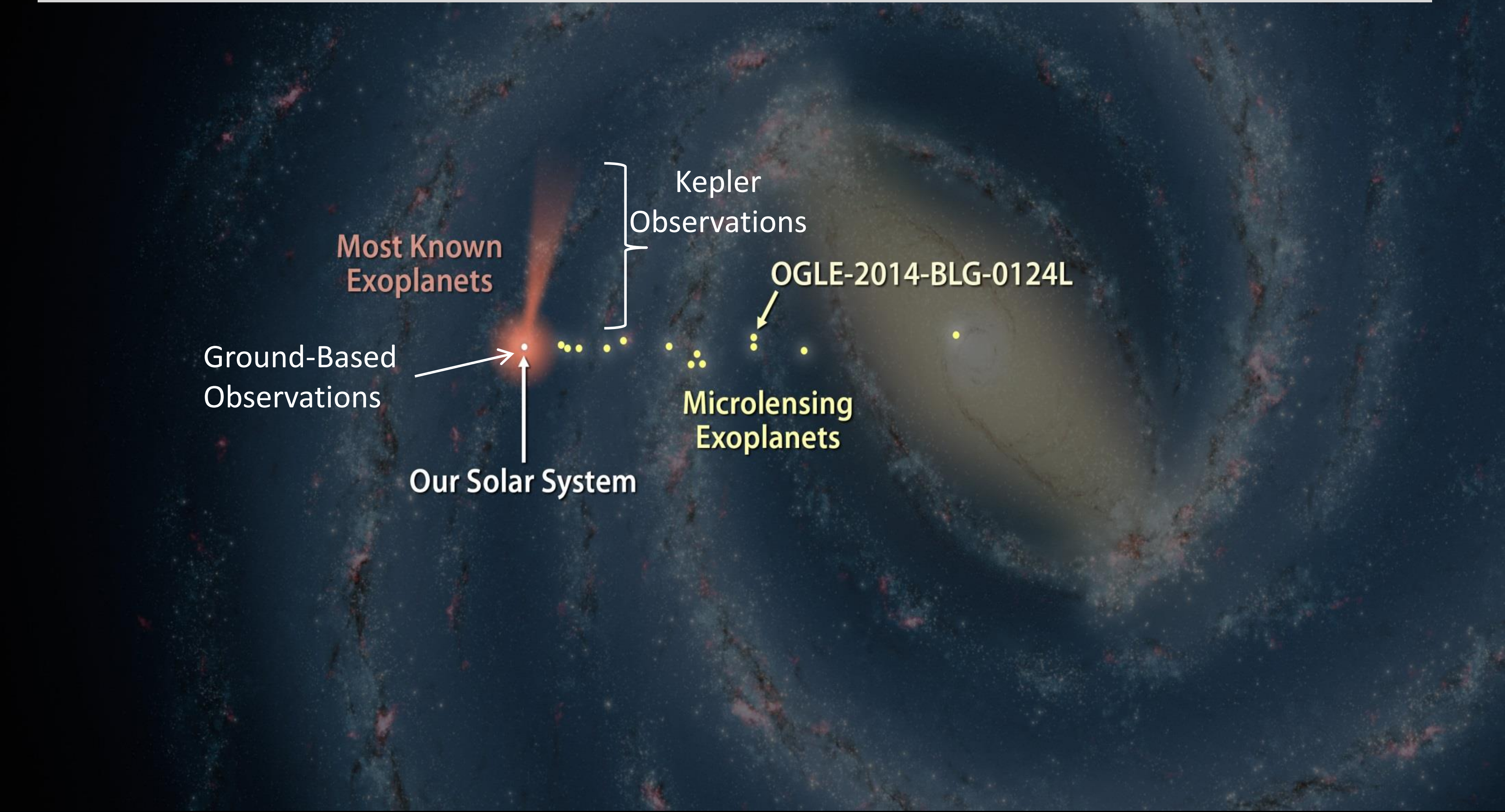
6. References

Opportunities for Contributions To Exoplanet Research

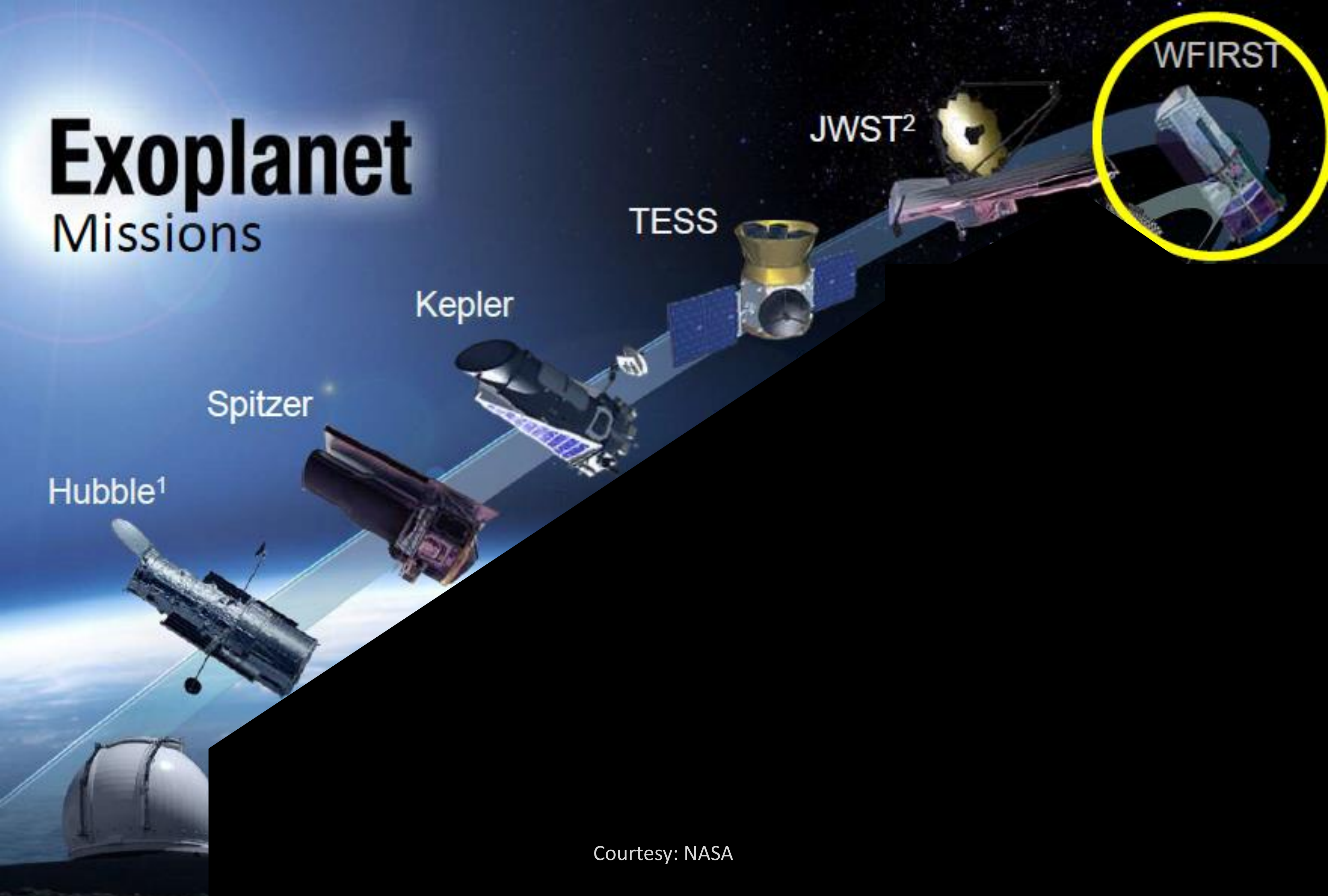
- Confirm new exoplanets – the KELT program
- Refine information about known exoplanets – the Hubble collaboration
- Help determine Transit Timing Variations – the ETD project
- Conduct private surveys

The Future

Until now, we are mostly looking in our immediate neighborhood!

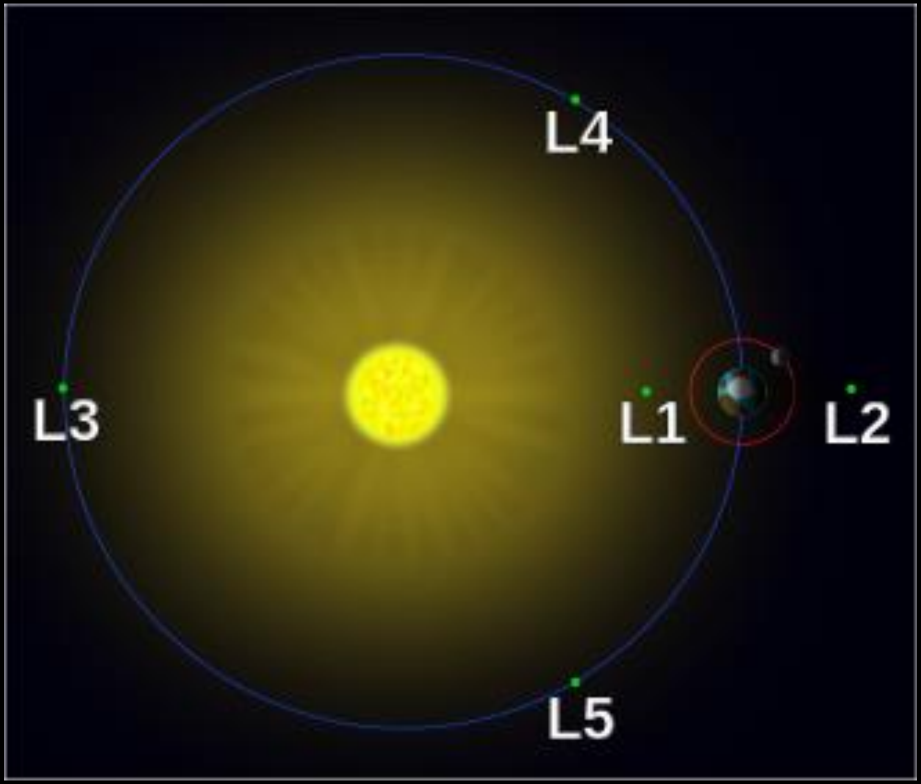


Courtesy NASA/JPL-Caltech

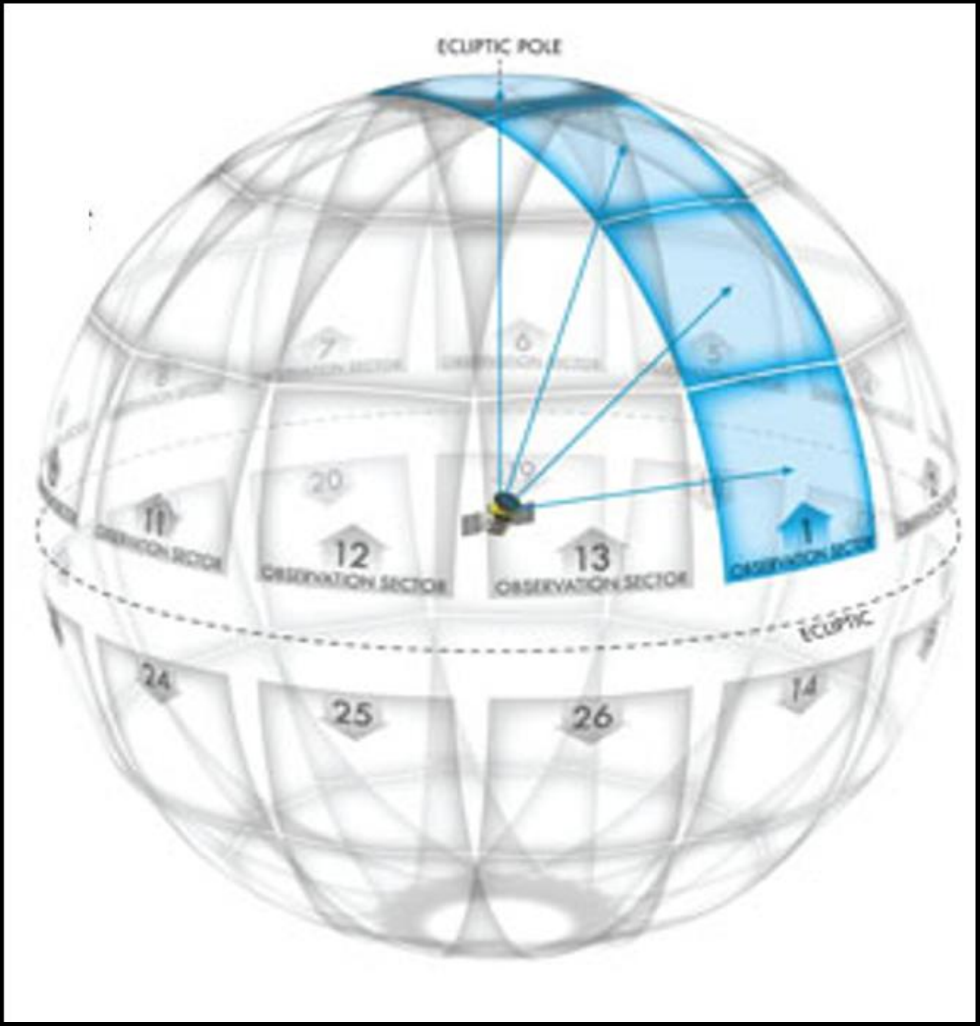


Courtesy: NASA

L2 Lagrange Point – The Future Home of JWST and WFIRST

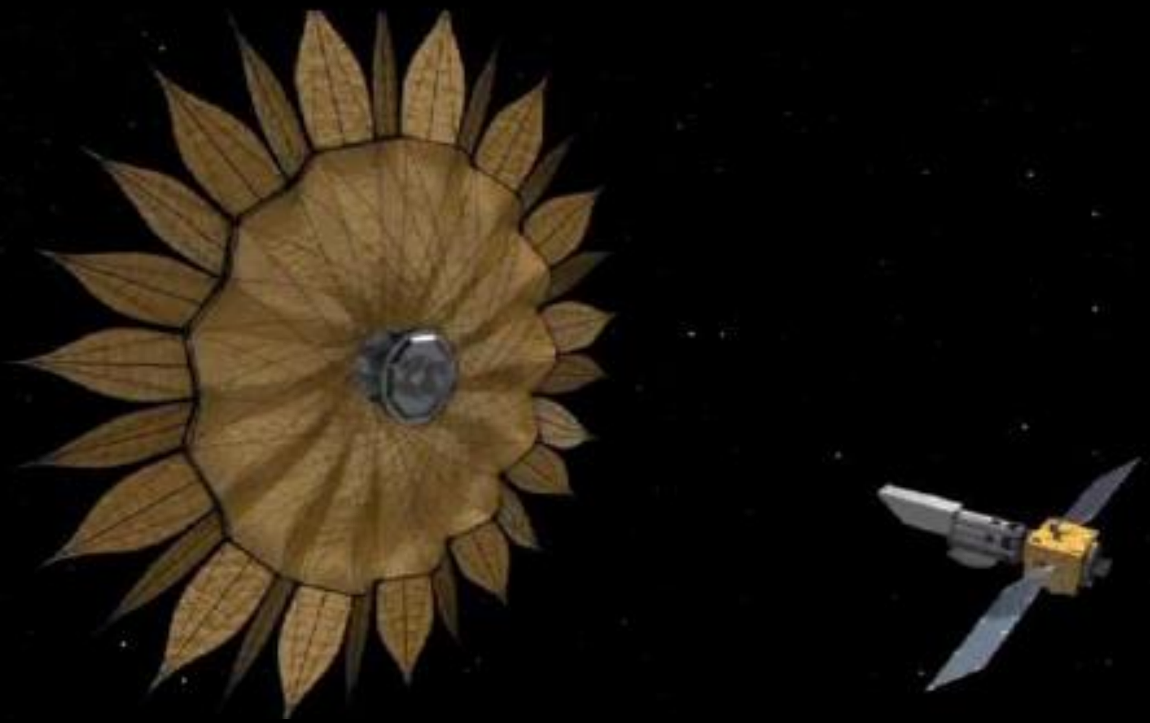


TESS Survey



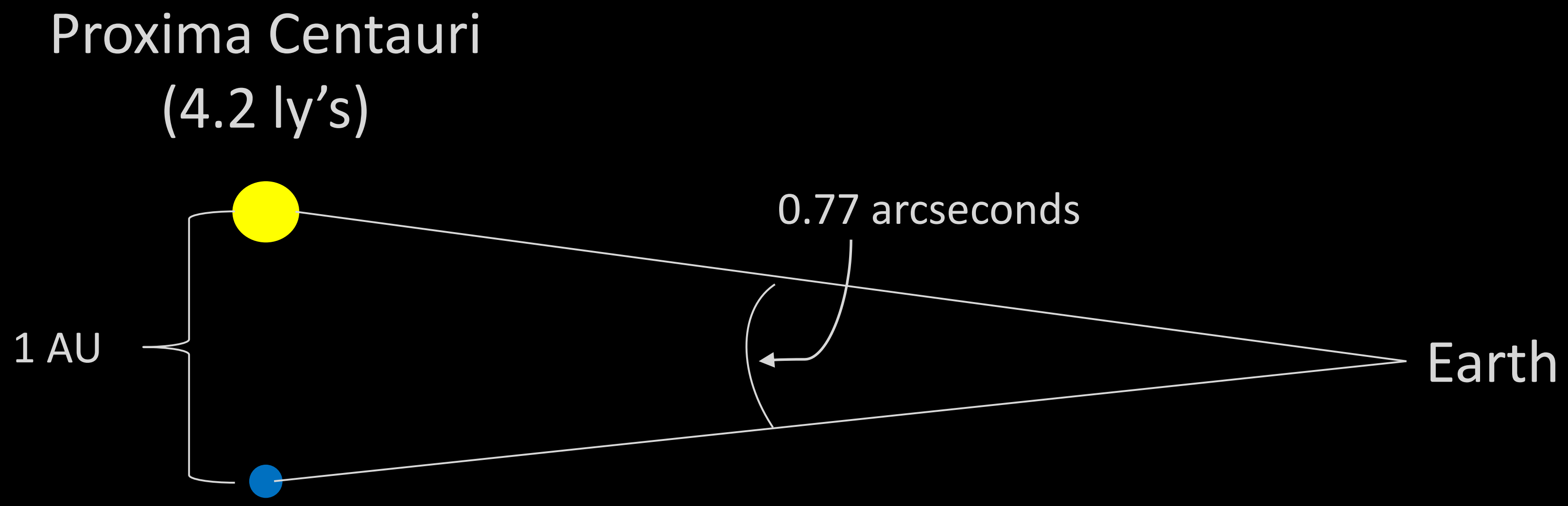
ECLIPTIC POLE
7
6
5
20
11
OBSERVATION SECTOR
12
OBSERVATION SECTOR
13
OBSERVATION SECTOR
1
OBSERVATION SECTOR
ECLIPTIC
24
25
26
14

Starshade Technology

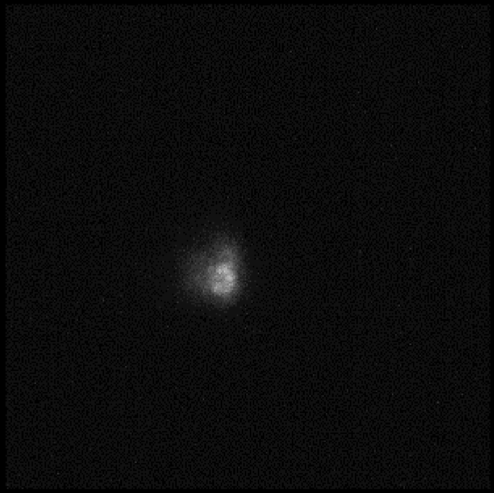


Courtesy: NASA

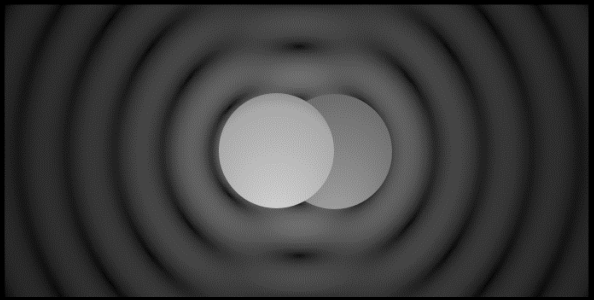
Will Amateur Astronomers be able to <u>directly</u> detect exoplanets?



Challenges



- Seeing limitations:
  atmospheric turbulence makes it difficult to differentiate both sources
  - (typical amateur astronomer seeing: 2-3 arcseconds)



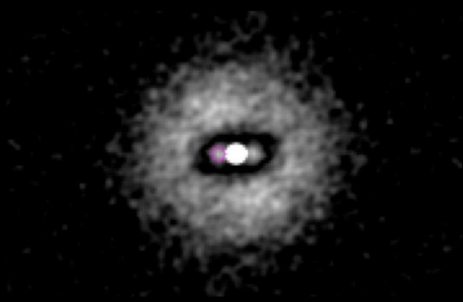
By Spencer Bliven - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=31456019

- Diffraction limitations:
  the wave nature of light produces an Airy disc pattern for both point sources
  - (Rayleigh criterion for a 14” aperture: 0.46 arcseconds)

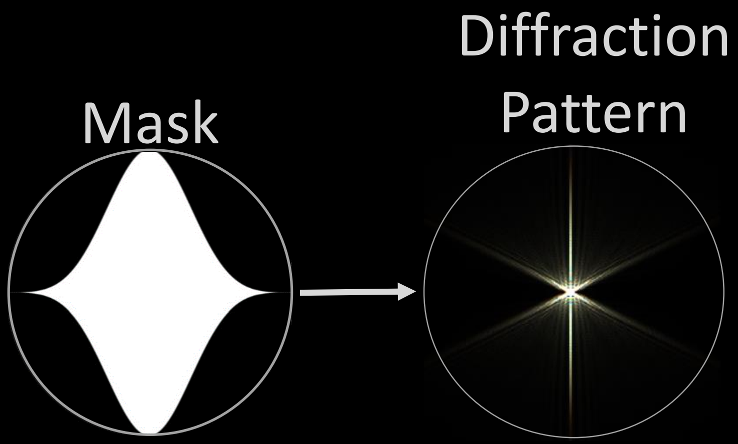
- Differential magnitude limitations:
  the extreme differences in magnitude between both objects makes it difficult to collect photons for the reflected light from the planet

Possible Solutions

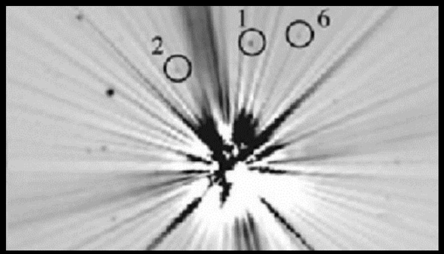
- Seeing limitations:
  speckle interferometry



- Diffraction limitations:
  shaped aperture masks



- Differential magnitude limitations:
  infrared cameras
  charge injection devices



Courtesy Daniel Batcheldor

Summary

- Amateur astronomers are able to conduct exoplanet transit observations with amazing accuracy
- Their contribution to exoplanet research continues to be of value to professional astronomers
- The need for such observations in the near future will continue to grow
- Amateur astronomers’ contribution to exoplanet research beyond just the transit method is promising

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

Addendum

Important AstroImageJ Terms

- T1: refers to target star
- Ci: refers to comparison star
- Source-Sky_xx: ADU counts in the aperture for star xx <u>after</u> the sky background is taken out (e.g., Source-Sky_C2)
- tot_C_cnts: the sum of the Source-Sky counts for all the comparison stars
- rel_flux_T1: the relative flux of target star T1
  = Source-Sky_T1/tot_C_cnts
- rel_flux_Ci: the relative flux of comp star Ci
  = Source-Sky_Ci/total cnts of all <u>other</u> C stars

AIJ Pipeline

Raw Bias, Dark, Flat Files   *Raw Science Images*

DP
(CCD Data Processing Function)

- Create master bias, dark, flat calibration files
- Calibrate Science images and optionally add FITS fields (e.g., BJD_TDB)

pipelineout_ files

cont'd

AIJ Pipeline (cont'd)

pipelineout_files

↓

Image Analysis

- Determine FWHM and initial Aperture/ Annulus radii using Alt-Left Click on target star
- Align images if necessary using Align Stack tool
- Eliminate "bad images"
- Select appropriate comp stars

↓

cont'd

AIJ Pipeline (cont'd)

Multi-Aperture Photometry

- Aperture settings:
  - ✓ Aperture/Annulus radii
  - ✓ CCD gain, readout noise, dark current
  - ✓ Saturation and linearity warning levels
- Place apertures
- When photometry completed, save Measurements table

cont'd

AIJ Pipeline (cont’d)

Multi-plot Main Screen

- Select BJD_TDB timebase in Default X-data
- Fill-in Title and Subtitle
- Fill-in Left and Right values for Fit and Normalize Regions (i.e., predicted ingress/egress times); copy them to V. Marker 1 and V. Marker 2
- Select Auto X Range and click on arrow
- If a meridian flip occurred during transit, click on Show and enter Flip Time

cont’d

AIJ Pipeline (cont'd)

Data Set 2 Fit Screen

- Enter predicted period
- Enter target star radius (R*)
- Enter predicted inclination (don't lock it)
- Enter limb darkening coefficients (u1 and u2) and lock them

cont'd

AIJ Pipeline (cont'd)

Multi-Plot Y Data Screen

- Plot AIRMASS vs. tot_C_cnts: will show changes in sky transparency
- Plot Source-Sky counts for target and comp stars: will show those with too much scatter
- Plot rel_flux of comp stars: will show those that might be variable; deselect those that are variable using the Multi-plot Reference Star Settings screen
- Plot rel_flux of target and its transit fit

cont'd

AIJ Pipeline (cont'd)

Data Set 2 Fit Screen

- If a meridian flip occurred during transit, select Meridian Flip as a detrend parameter
- Set detrend parameters (at most 3) that result in a reduction in BIC by more than 5 (start with AIRMASS)
- Sequentially deselect comp stars until a minimum RMS is obtained
- See "A Practical Guide to Exoplanet Observing" for further optimization guidelines and how to create a dataset for input to external programs