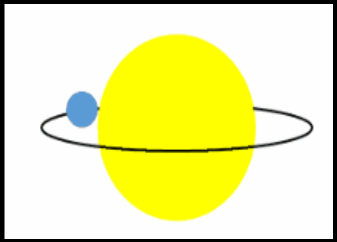


The Role of Amateur Astronomers in Exoplanet Research

Dennis M. Conti
Chair, AAVSO Exoplanet Section

Overview

- Contributions To-Date
- Technical Capabilities and Techniques Used
- HST Collaboration
- Lessons Learned
- Direct Exoplanet Detection and Imaging
- What the Future Holds

Background

- Amateur astronomers primarily use the transit method
- Some successful attempts at RV measurements (to 50m/sec) and microlensing observations
- Direct imaging currently not possible due to seeing and diffraction limiting factors
- Observations also include other “exo-objects” – e.g., disintegrating planetesimals (WD-1145)

Contributions To-Date

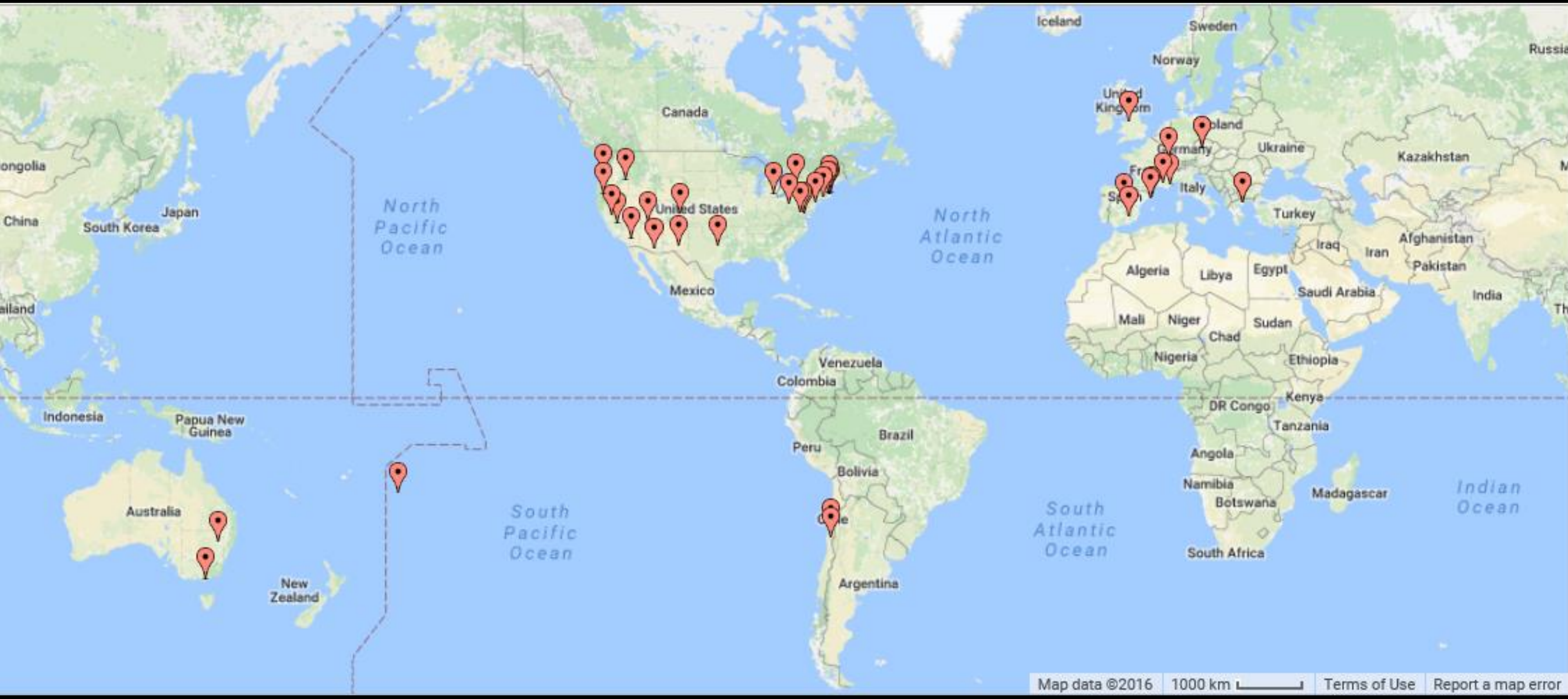
- Confirm new exoplanets – the KELT program
- Refine the ephemeris of known exoplanets – an HST collaboration
- Help extend the baseline of tertiary eclipse models by conducting Eclipse Timing Variations (ETVs)
- Conduct private surveys

Capabilities

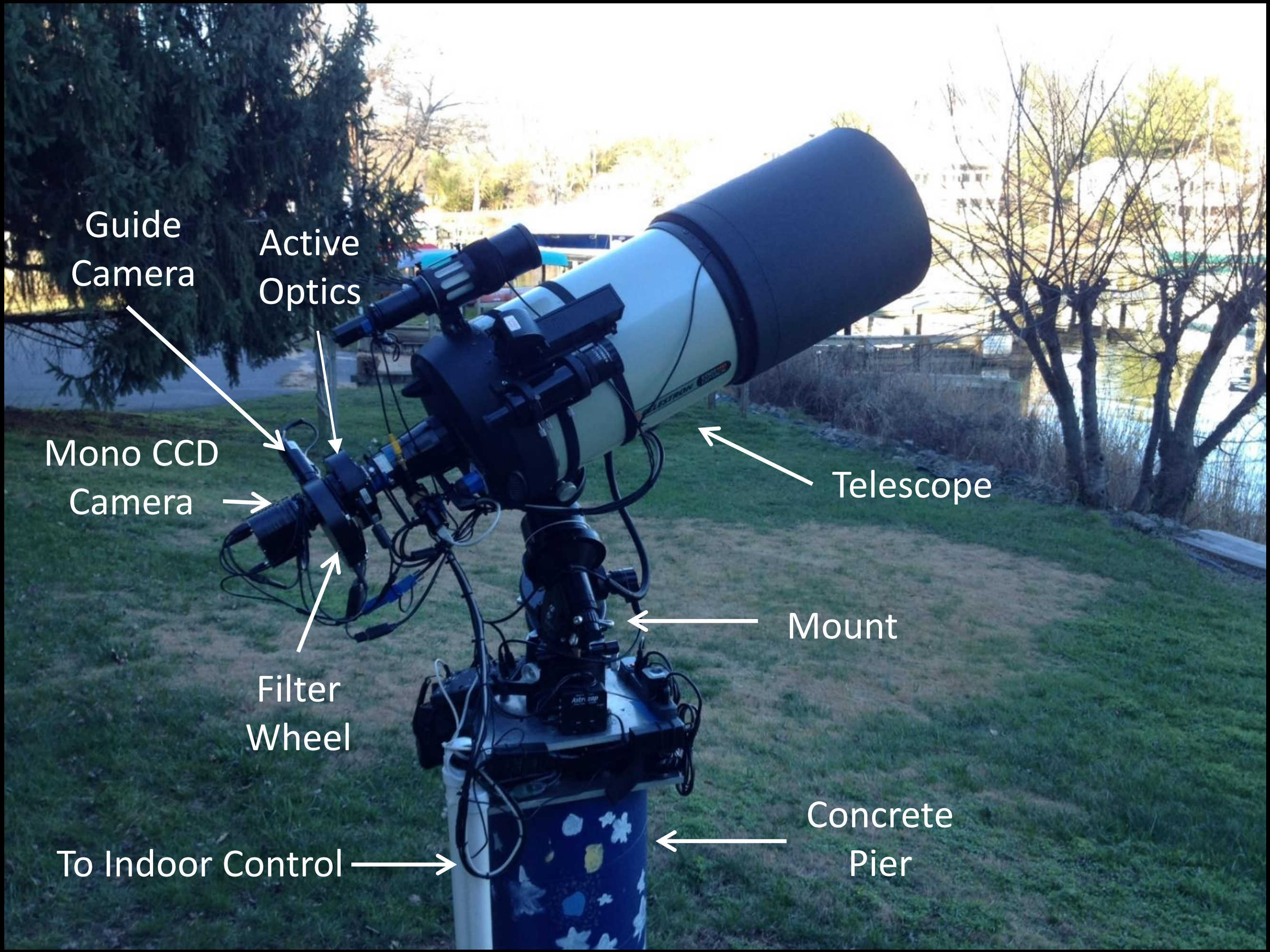
Observations

- Transit depths detectable to 2 mmag (>10 mmag more typical)
- Alternating use of filters to distinguish eclipsing binaries from exoplanets
- Simultaneous observations can better refine ephemeris
- Same equipment used for deep sky imaging can easily be adapted to exoplanet observing

World-Wide Network of Observers

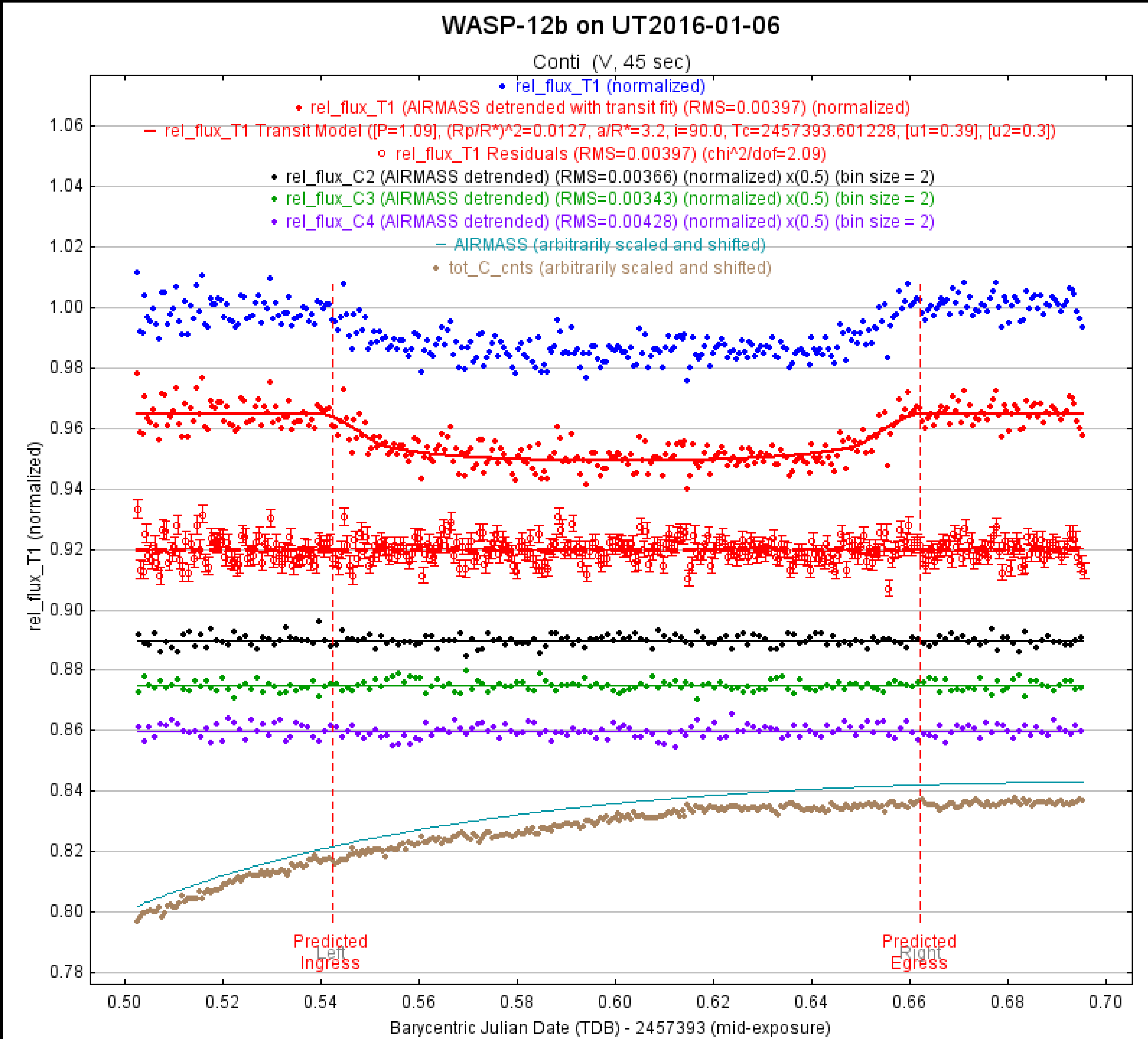


Typical Setup
Location: Suburban Annapolis, MD

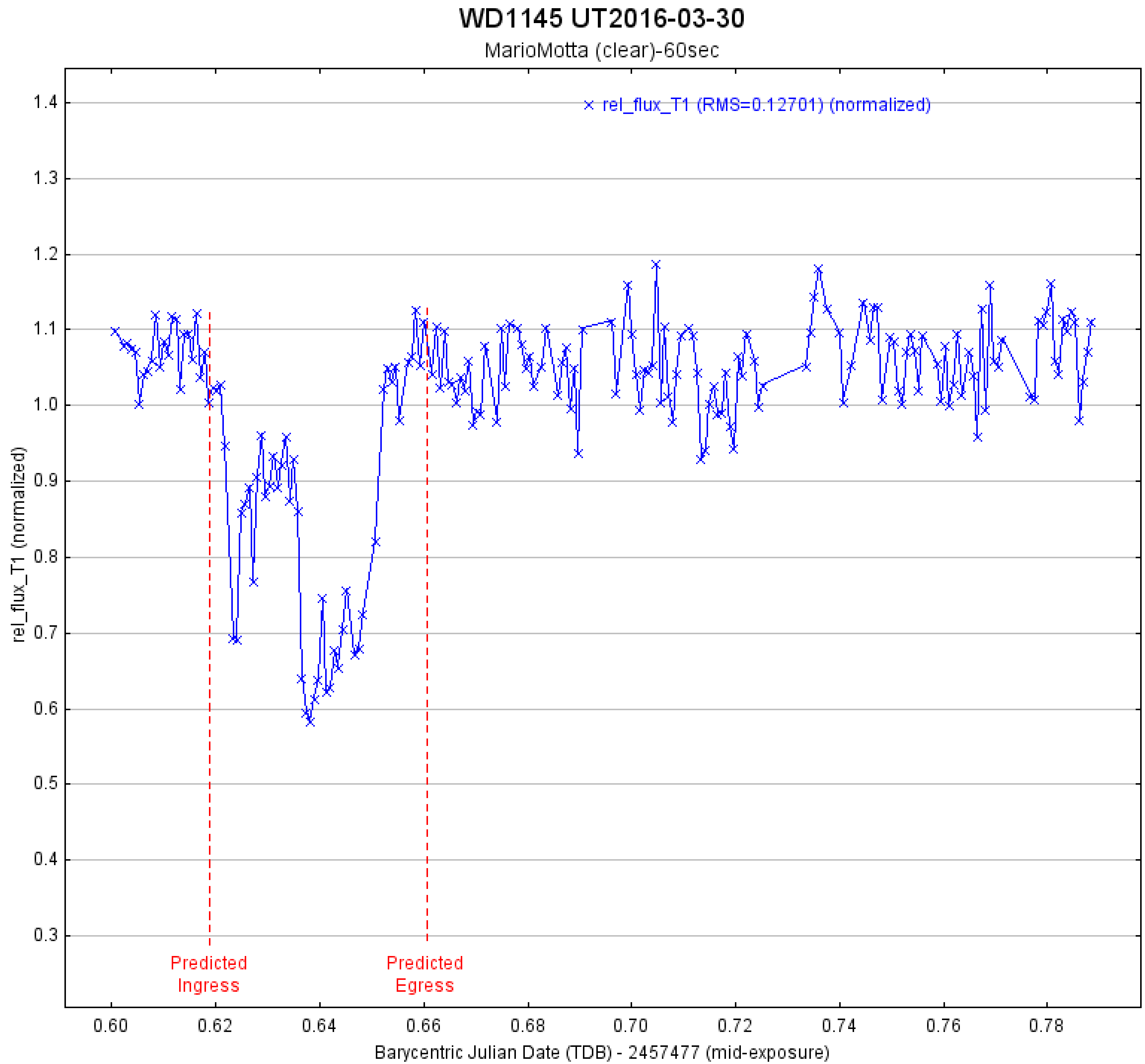


Techniques

- High precision, differential photometry employed
- Demands uniform flat-fielding, precise guiding, and accurate timing
- All-in-one software (AstroImageJ) can be used for calibration, differential photometry and transit modeling

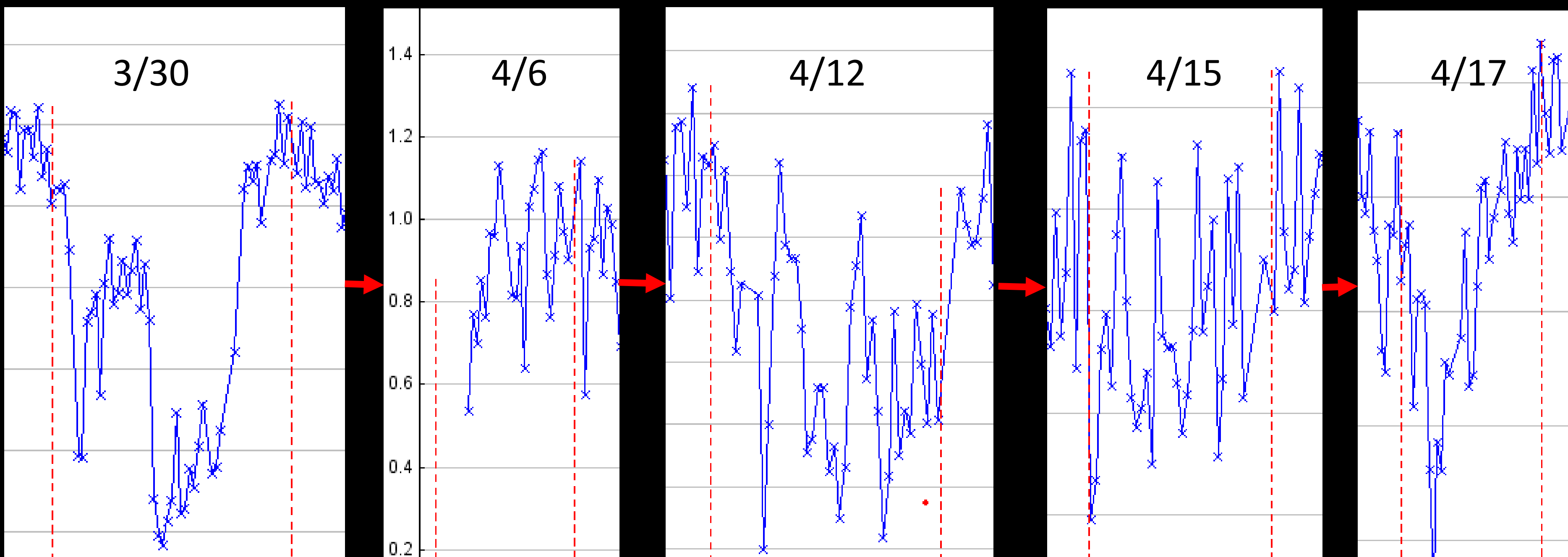


WASP-12b on UT2016-01-06
Conti (V, 45 sec)
rel_flux_T1 (normalized)
rel_flux_T1 (AIRMASS detrended with transit fit) (RMS=0.00397) (normalized)
rel_flux_T1 Transit Model ([P=1.09], (Rp/R*)^2=0.0127, a/R*=3.2, i=90.0, Tc=2457393.601228, [u1=0.39], [u2=0.3])
rel_flux_T1 Residuals (RMS=0.00397) (chi^2/dof=2.09)
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)
Predicted Left Ingress
Predicted Right Egress
Barycentric Julian Date (TDB) - 2457393 (mid-exposure)



WD1145 UT2016-03-30
MarioMotta (clear)-60sec
rel_flux_T1 (RMS=0.12701) (normalized)
Predicted Ingress
Predicted Egress
rel_flux_T1 (normalized)
Barycentric Julian Date (TDB) - 2457477 (mid-exposure)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
0.78

WD-1145+017 Observations



Courtesy of Mario Motta

HST Collaboration

- Purpose of HST program #14260:

  > "Using the water molecule as a probe, we will investigate the degree to which planetary envelopes are enriched in heavy elements as a function of planetary mass, and how that enrichment might be affected by mass loss.
  >
  > We will define the degree to which clouds occur in exoplanetary atmospheres, over a wide range in temperature, surface gravity, and stellar irradiation."

- Drake Deming is PI, along with several co-investigator's

- 15 exoplanets being observed, some multiple times

- HST's WFC3/IR camera used

Status

- HST has completed 20 of 23 visits
- Role of amateur astronomers is to help refine ephemeris
- Over 60 high-quality, ground-based observations have been made to-date
- A “Practical Guide to Exoplanet Observing” developed
  - provides best practices and a tutorial on AstroImageJ

Pipeline

- An updated, prioritized list of targets is regularly posted
- Observers post light curves and initial modeling results
- Promising observations are re-reduced in a standard way, using the original images, and a transit model fit is performed; BJD_{TDB} time base used
- If the re-reduction looks good, results are scheduled for inclusion in a global fit
- A global fit, with best detrend parameters, is conducted for both circular and eccentric orbits

Sample Global Fit Output

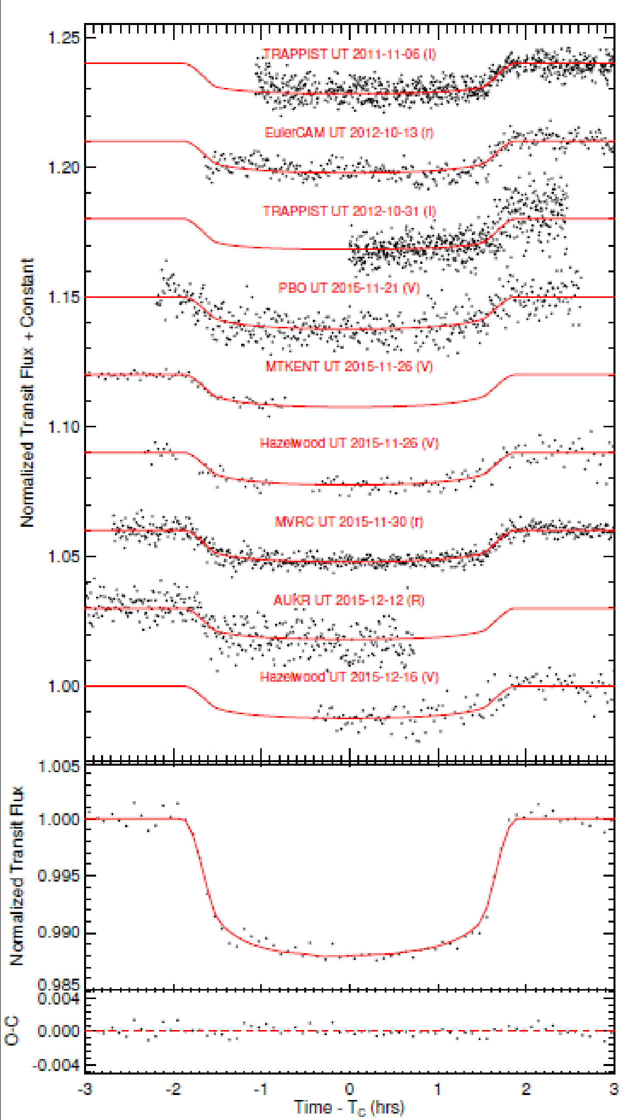


TABLE 3

MEDIAN VALUES AND 68% CONFIDENCE INTERVAL FOR THE PHYSICAL AND ORBITAL PARAMETERS OF THE WASP-76B SYSTEM

Parameter	Units	Adopted Value(Torres circular)	Value(Torres eccentric)
Stellar Parameters			
M_*	Mass ($M_\odot$)	$1.370^{+0.072}_{-0.069}$	$1.369^{+0.070}_{-0.069}$
R_*	Radius ($R_\odot$)	$1.693^{+0.032}_{-0.031}$	$1.682^{+0.039}_{-0.040}$
L_*	Luminosity ($L_\odot$)	$4.10^{+0.34}_{-0.32}$	$4.03^{+0.35}_{-0.33}$
ρ_*	Density (cgs)	$0.3993^{+0.0071}_{-0.0087}$	$0.406^{+0.018}_{-0.016}$
$\log g_*$	Surface gravity (cgs)	$4.1177^{+0.0092}_{-0.0098}$	$4.123^{+0.014}_{-0.013}$
$T_{\rm eff}$	Effective temperature (K)	6315^{+94}_{-93}	6313^{+93}_{-92}
[Fe/H]	Metallicity	$0.202^{+0.096}_{-0.095}$	$0.206^{+0.096}_{-0.097}$
Planet Parameters			
e	Eccentricity	—	$0.0124^{+0.013}_{-0.0086}$
ω_*	Argument of periastron (degrees)	—	-51^{+82}_{-67}
P	Period (days)	$1.80988211 \pm 0.00000069$	$1.80988245 \pm 0.00000068$
a	Semi-major axis (AU)	$0.03228^{+0.00056}_{-0.00055}$	$0.03227^{+0.00054}_{-0.00055}$
M_P	Mass (M_J)	$0.873^{+0.038}_{-0.036}$	0.893 ± 0.034
R_P	Radius (R_J)	$1.669^{+0.034}_{-0.033}$	$1.656^{+0.040}_{-0.041}$
ρ_P	Density (cgs)	$0.2333^{+0.0094}_{-0.0097}$	$0.244^{+0.015}_{-0.013}$
$\log g_P$	Surface gravity	2.890 ± 0.013	$2.906^{+0.017}_{-0.016}$
T_{eq}	Equilibrium temperature (K)	2205^{+33}_{-32}	2197 ± 35
Θ	Safronov number	$0.02463^{+0.00076}_{-0.00075}$	$0.02539^{+0.00084}_{-0.00078}$
$\langle F \rangle$	Incident flux (10^9 erg s^{-1} cm^{-2})	$5.36^{+0.33}_{-0.31}$	$5.29^{+0.35}_{-0.33}$
RV Parameters			
T_C	Time of inferior conjunction (BJD_{TDB})	$2457059.85251 \pm 0.00026$	$2457059.85240^{+0.00027}_{-0.00026}$
T_P	Time of periastron (BJD_{TDB})	—	$2457060.95^{+0.41}_{-0.35}$
K	RV semi-amplitude (m/s)	118.0 ± 2.8	120.7 ± 2.1
$M_P \sin i$	Minimum mass (M_J)	$0.872^{+0.038}_{-0.036}$	$0.892^{+0.035}_{-0.034}$
M_P/M_*	Mass ratio	0.000608 ± 0.000018	$0.000623^{+0.000016}_{-0.000015}$
u	RM linear limb darkening	$0.6081^{+0.0096}_{-0.0088}$	$0.6085^{+0.0097}_{-0.0088}$
$\gamma_{CORALIE}$	m/s	-1074 ± 29	-1081 ± 13
γ_{SOPHIE}	m/s	-1047 ± 38	-1057 ± 17
$\dot{\gamma}$	RV slope (m/s/day)	0.021 ± 0.032	0.013 ± 0.014
$e \cos \omega_*$		—	$0.0038^{+0.010}_{-0.0065}$
$e \sin \omega_*$		—	$-0.0029^{+0.0086}_{-0.015}$
Linear Ephemeris from Follow-up Transits:			
P_{Trans}	Period (days)	1.8098821 ± 0.0000007	—
T_0	Linear ephemeris from transits (BJD_{TDB})	$2457059.852529 \pm 0.000267$	—

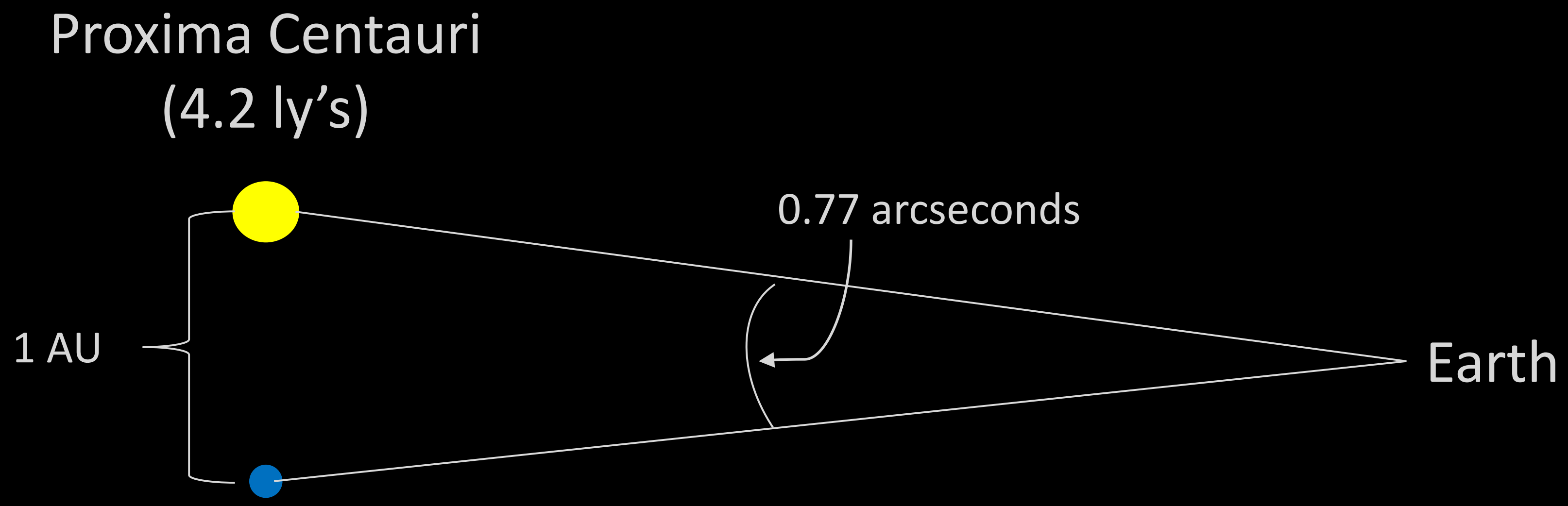
(cont'd)

Key Lessons Learned

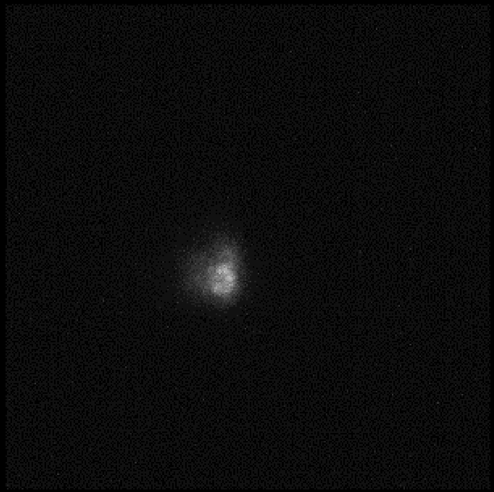
- Need way to scale initial qualification and follow-up reduction to support large scale future surveys (e.g., TESS, JWST)
- Need better training tools to push quality closer to original observers
- Need a database to store and later retrieve light curve data

Direct Detection and Imaging: Challenges and Potential Solutions

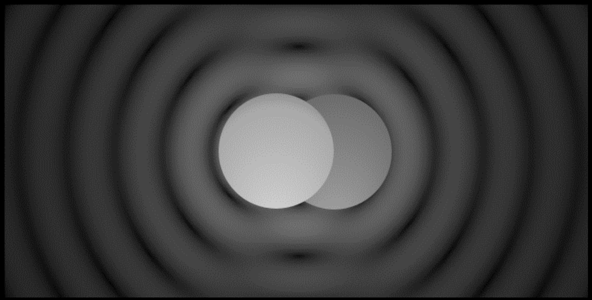
Will Amateur Astronomers be able to <u>directly</u> detect exoplanets?



Challenges



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



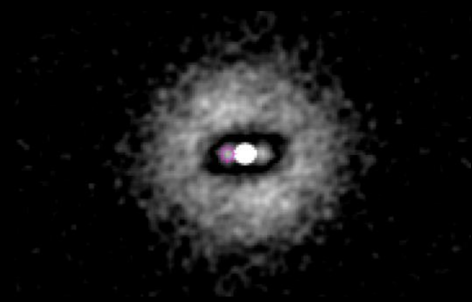
By Spencer Bliven - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=31456019

- 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)

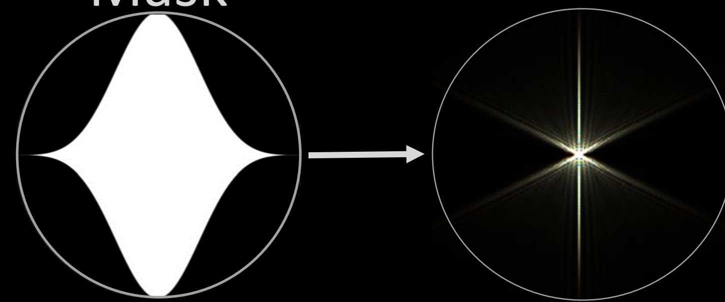
- Differential magnitude limitations:
  the extreme differences in magnitude between both objects makes it difficult to collect photons for the reflected light from the planet

Possible Solutions

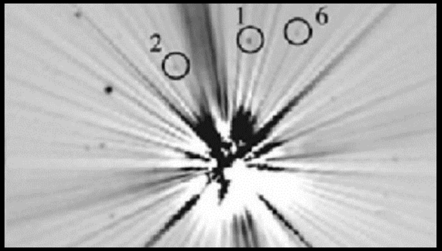
- Seeing limitations:
  speckle interferometry



- Diffraction limitations:
  shaped aperture masks



- Differential magnitude limitations:
  charge injection devices



The Future

- The need for follow-up observations will continue to grow with upcoming space-based surveys (TESS, JWST)
- Contribute to TTV timings of hot Jupiters with close-in companions (see Becker, et al., 2015)
- The AAVSO is developing a repository for amateur astronomer exoplanet observations
- Amateur astronomers continue to explore techniques for direct exoplanet imaging/detection
- Observatories at educational institutions offer another source of exoplanet observations: just need training and coordination

Summary

- A network of amateur astronomers is available to the professional community for conducting transit observations
- Benefits:
  - the global network maximizes temporal and sky coverage
  - different campaigns can be quickly supported
  - simultaneous observations of a given target can be scheduled – mitigates weather issues and allows for comparative observations with different filters
  - observing time is economical (free!)
- Amateur astronomers are available to test new direct imaging and detection techniques

Links

- www.astrodennis.com
  - "A Practical Guide to Exoplanet Observing"
- www.aavso.org/exoplanet-section