Exoplanet Atmosphere and TTV Science with Sub-meter Class Telescopes

Karen Collins*

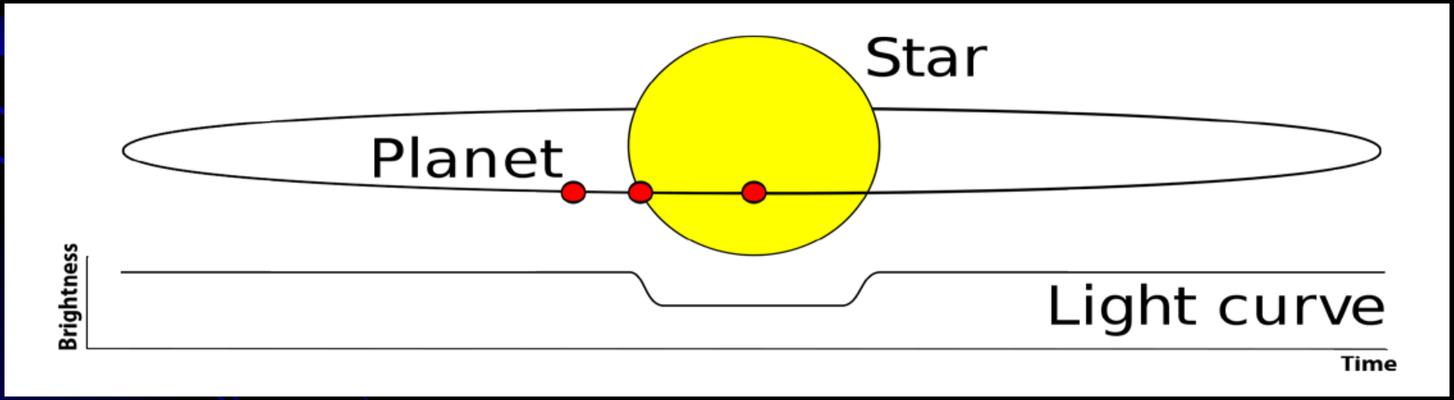
University of Louisville

Department of Physics and Astronomy

*Supported by a NASA Kentucky Space Grant Consortium Fellowship

Transiting Exoplanet

- Planet passes through the line of sight from Earth to the exoplanet's parent star, blocking part of the star's flux from our perspective
- Using photometry we can measure the slight change in the host star's apparent brightness
- Geometric constraints limit the probability of occurrence (~10% for close-in orbits) (~ 0.5% for Earth-size at 1 AU)



Research Goals

- Better characterization of known transiting exoplanets through light curve fitting of multiple transits
- Possible discovery of new exoplanets through the measurement of transit timing variations
- Characterization of the atmospheres of known transiting exoplanets through observations of the atmosphere’s transmission spectrum
- Follow-up photometry for wide field transit surveys

Our Challenges

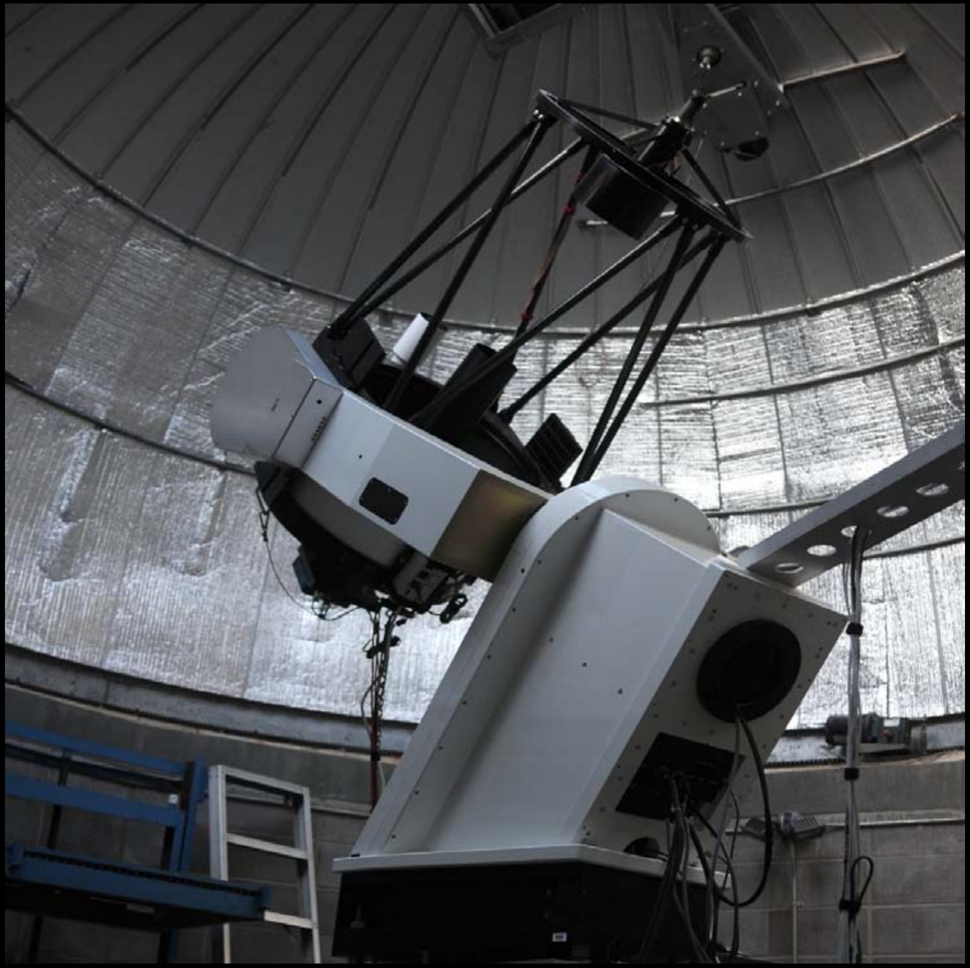
- Limited telescope apertures (50 – 70 cm)
- Moore observatory in Louisville is at an elevation of 22,900 (centi)meters
- Sky transparency not always favorable
- Sky brightness is moderate due to Louisville city lights to the west
- Weather could be better

But !

- We have dedicated telescopes (soon to be 4) near research staff (2 northern hemisphere, 2 southern hemisphere)
- We do have ~80 clear nights each year at Moore
- Photometric noise due to seeing is reduced at our usual 40-60 sec exposure times
- With ~100 known transiting exoplanets bright enough for us to reach ~1 mmag/min precision, targets are available on most every clear night
- => about ~50 high precision light curves per year per telescope

Northern Hemisphere
(Moore Observatory – Louisville, KY)

- RC24 60 cm telescope
- Routinely used for transit observing
- Ritchie-Chretien design
- Field-of-view 26’ x 26’
- Apogee U16M CCD with 4096x4096 array of 9 micron pixels
- Pixel scale 0.39 arcsec
- Sloan filter set (g’, r’, z’, I’) + NB filters



- Very smooth tracking, no meridian flip required, no zenith limitations

Northern Hemisphere
(Moore Observatory – Louisville, KY)

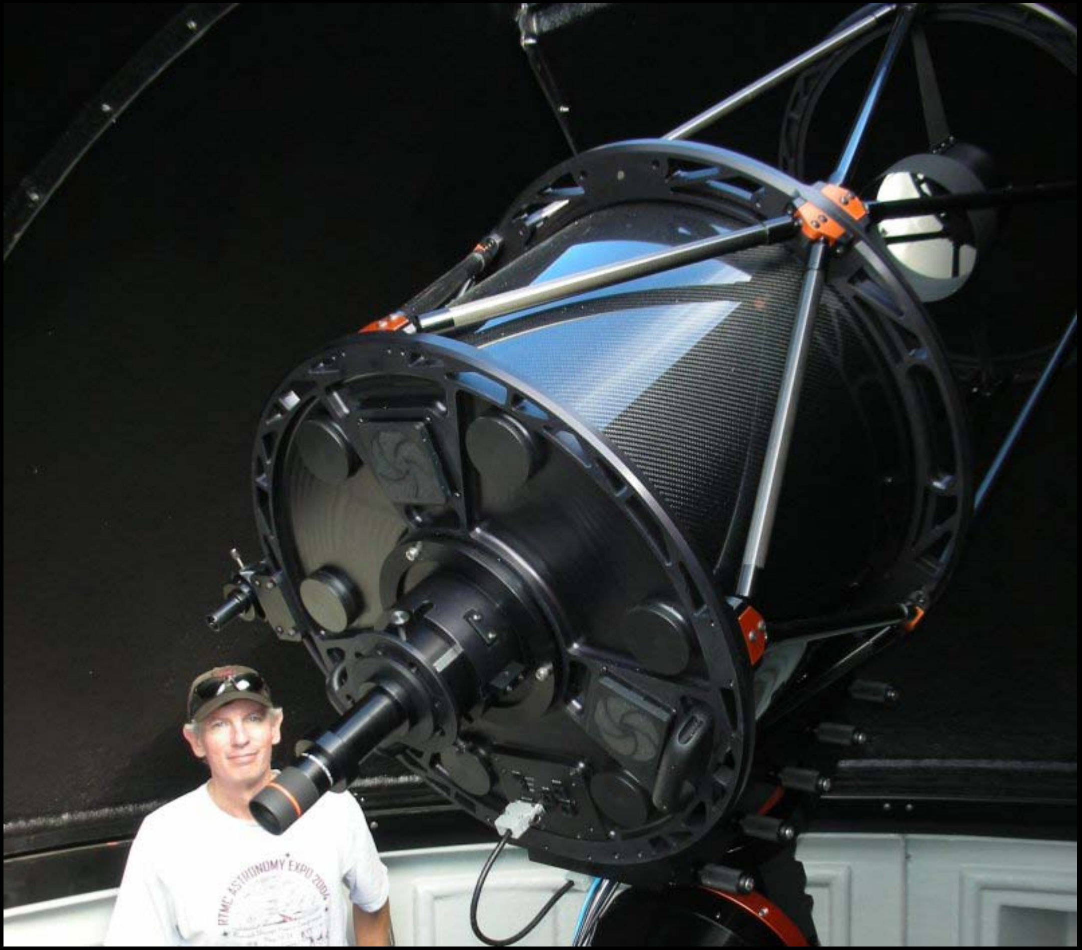
- Planewave 50 cm telescope
- Corrected Dall-Kirkham (2 mirror + lens group)
- Field-of-view 37’ x 37’
- Apogee U16M CCD with 4096x4096 array of 9 micron pixels
- Pixel scale 0.54 arcsec
- Sloan filter set (g’, r’, z’, I’) + NB filters
- Remote operation capability

- Original mount had unpredictable tracking error – replacing now with high quality mount

Southern Hemisphere

(Mt. Kent Observatory near Toowoomba, Queensland, Australia)

- UofL and USQ are part of the Shared Skies initiative to bring live observing into the classroom



- Planewave 50 cm telescope
- Same capability as Moore Observatory 50cm
- Same mount problem, will be corrected and available early 2012

Southern Hemisphere

(Mt. Kent Observatory near Toowoomba, Queensland, Australia)

- Mt. Kent has better observing conditions than Moore observatory

- CDK700 70 cm telescope
- Corrected Dall-Kirkham (2 mirror + lens group)
- Similar capability to RC24 at Moore
- Available early 2012

Transit Science is a Good fit for our Instrumentation

- Lots of telescope time available
- Telescope apertures large enough to enable 1 mmag/min photometry
- Excellent tracking on the RC 24 (and others soon) makes guiding simple and precise
- CCDs significantly oversample PSF creating larger photon buckets
- Observatories in both hemispheres provide full sky coverage

Observing a Transiting Exoplanet - The Standard Stuff -

- Optimize exposure cadence by minimizing:
  - photons lost due to CCD readout time
  - sky background (vs. defocusing) (see Howell 2000 & Southworth et al. 2009)
  - read out noise
  - scintillation noise (see Young et al. 1967)
- Spend as much time observing out-of-transit as in-transit
  - provides good data for airmass/color detrending
  - reduces light curve modeling error bars
- Defocus telescope to spread light over many pixels
  - reduces intra-pixel variation effects resulting from guiding errors
  - Improves “dynamic range” available for comparison stars
  - But, must be careful with sky background and blending
- Point telescope to maximize comparison star availability
  - SKY-MAP.org with DSS2 imagery is an excellent tool for this purpose with its click and drag color imagery

Theory in Practice in Louisville

- A good appreciation of the theoretical best exposure time and level of defocus is imperative, BUT …
- Our sky conditions are unpredictable and change throughout the night
- We need to be able to optimize exposure time and defocusing in "real time" (i.e. as we are observing)
- Even with flat-fielding and guiding to within 3-5 pixels, deep "dust donuts" will introduce systematic noise if not avoided

➔ We need real time data reduction and light curve plotting capability

A Review of Real-Time Data Reduction Tool Requirements

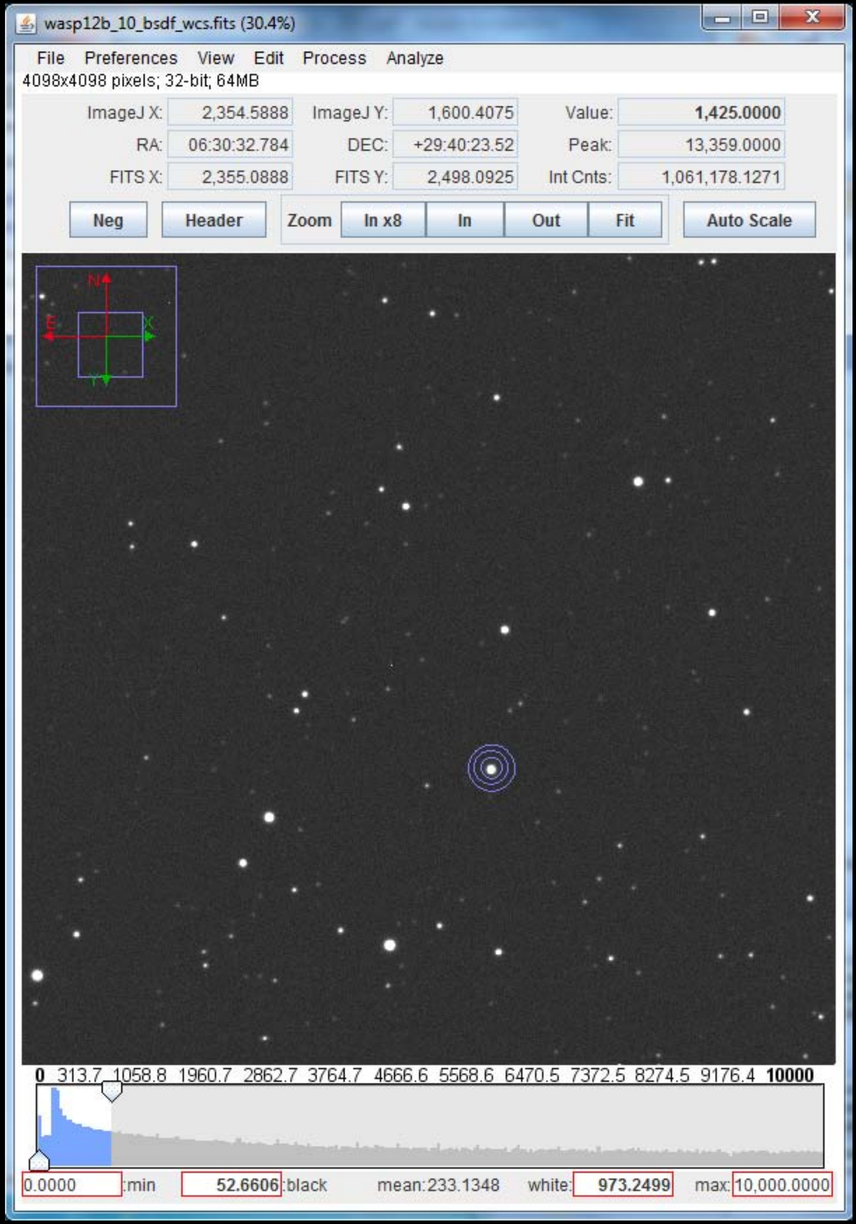
- Bias Subtraction
- Dark Subtraction
- Flat-field Division
- CCD non-linearity correction
- Aperture Photometry
- Differential Aperture Photometry
- Light curve plotting
- Plot parameter adjustment

Our Solution - AstroImageJ

- Based on ImageJ
  - Open source, public domain, image processing program developed at the National Institutes of Health
  - Java-based, so runs on all computing platforms
- Also based on a set of Astronomy “plugins” originally developed by Rick Hessman at Institut für Astrophysik Göttingen
- We have significantly extended ImageJ & Astronomy plugins resulting in an open source, public domain package called **AstroImageJ**
- AstroImageJ is available for download at http://www.astro.louisville.edu/software/astroimagej/

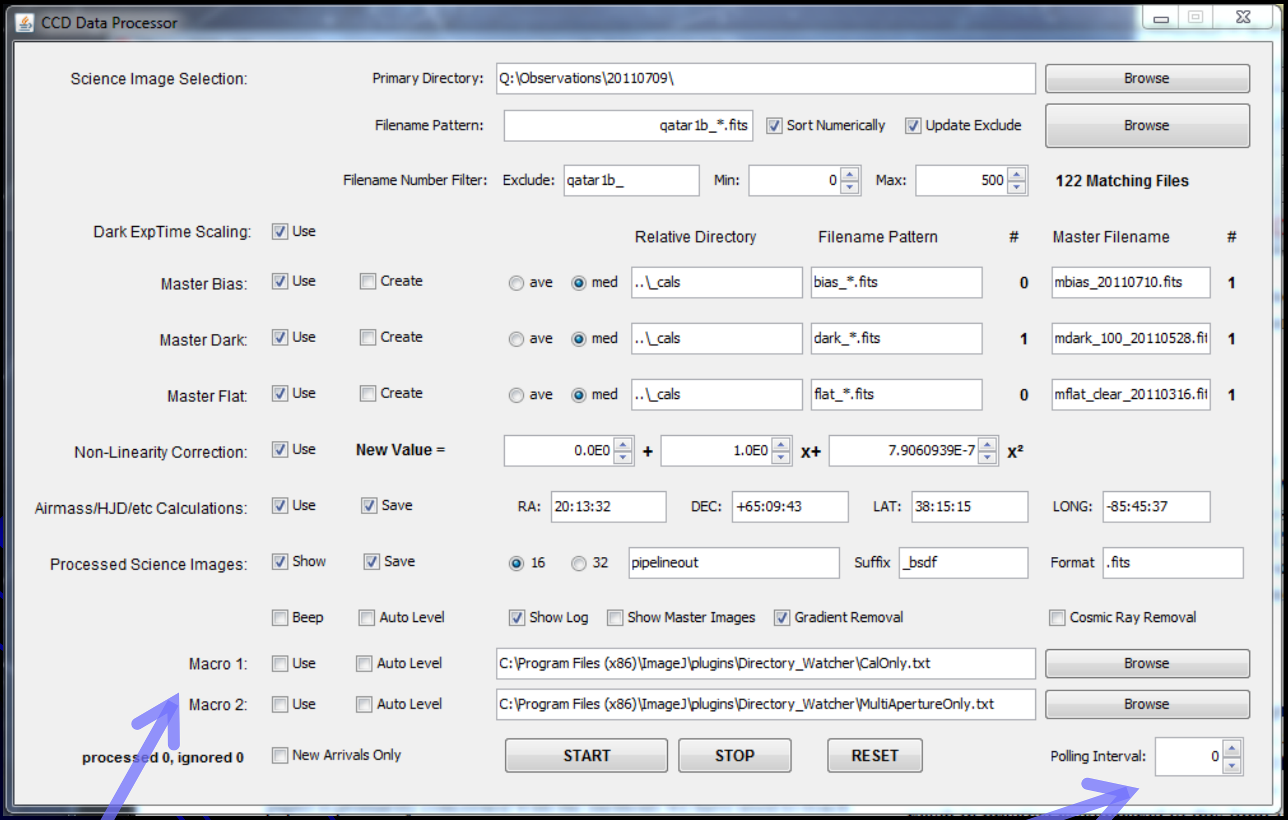
DS9-like Image Display

- AstroImageJ provides a DS9-like user interface
- Live photometer
  - Peak count
  - Integrated counts
- Supports WCS
- Efficient Image Control
  - Contrast
  - Zooming
  - panning



Data Processor Module

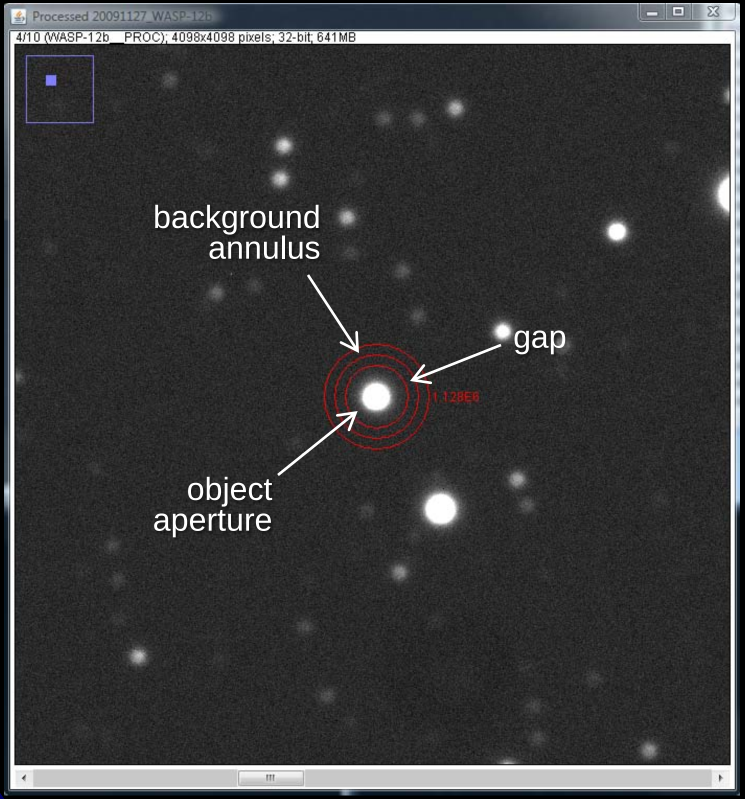
- AstroIJ provides a GUI interface for master calibration file creation and basic data reduction



- Polling capability to monitor for new images from the CCD
- Macros run the Multi-photometer and Multi-plot modules

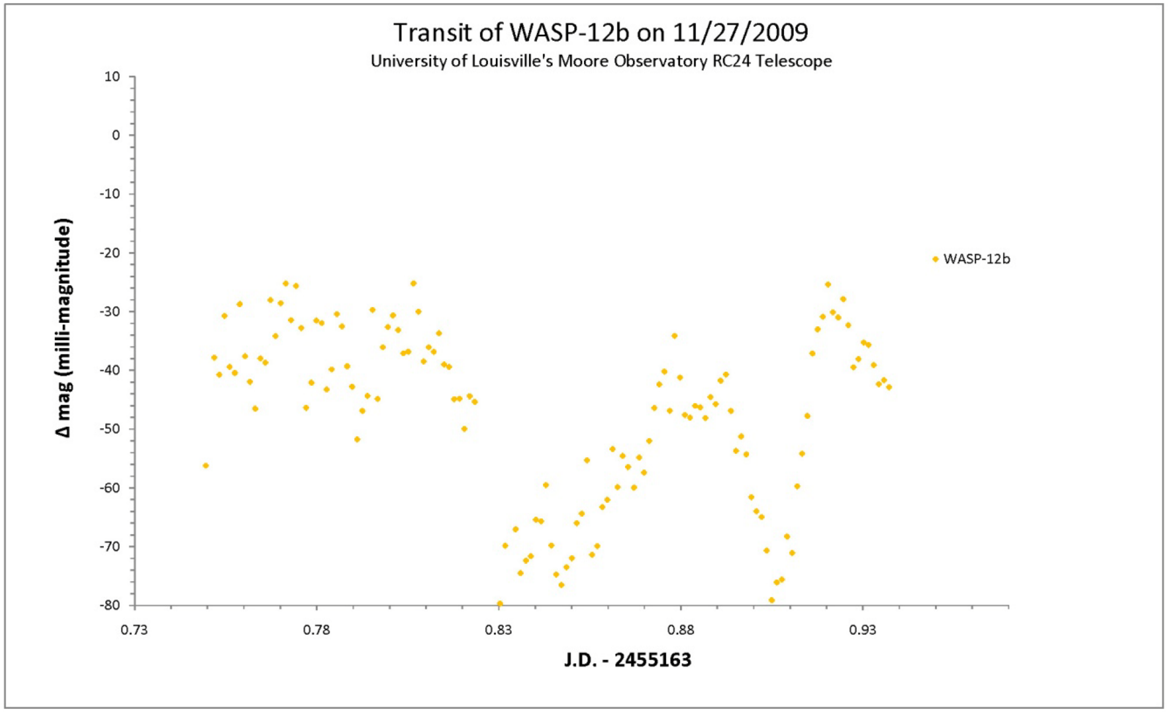
Simple Aperture Photometry

Integrates all CCD pixel counts in a region near a star and subtracts sky background from outer annulus



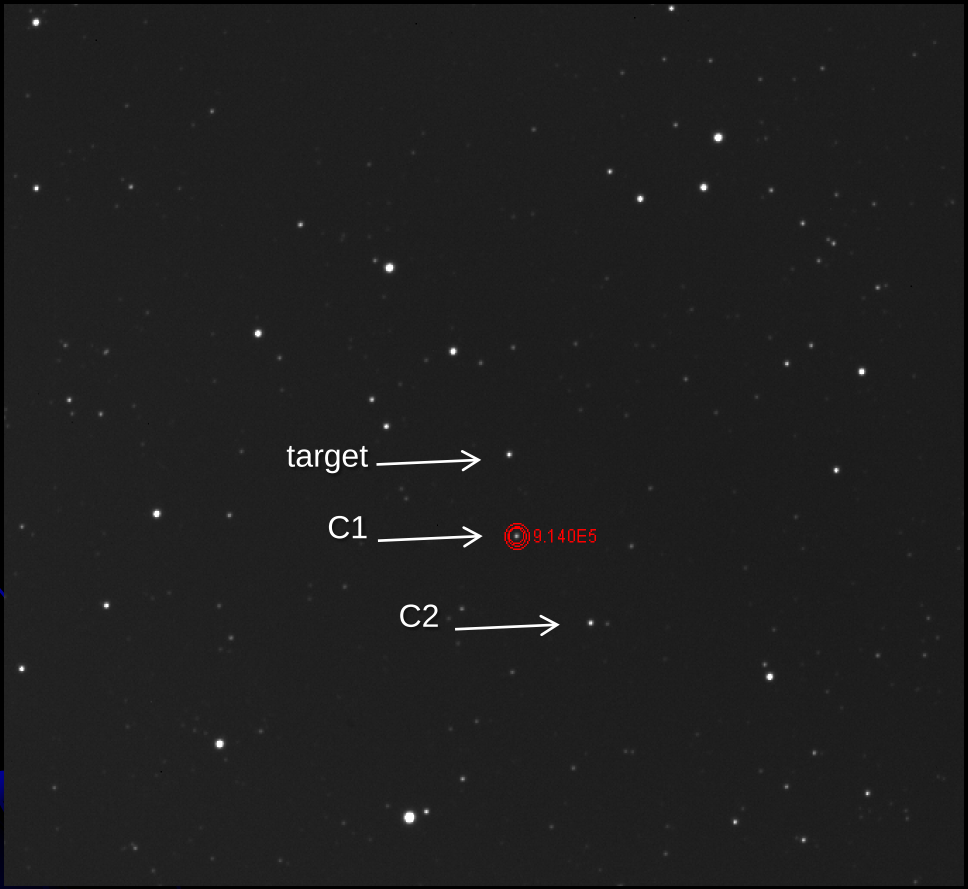
Example Resulting Light Curve

- A plot of the net integrated target counts in each exposure vs. time
- Can you identify the transit through Louisville's atmosphere?



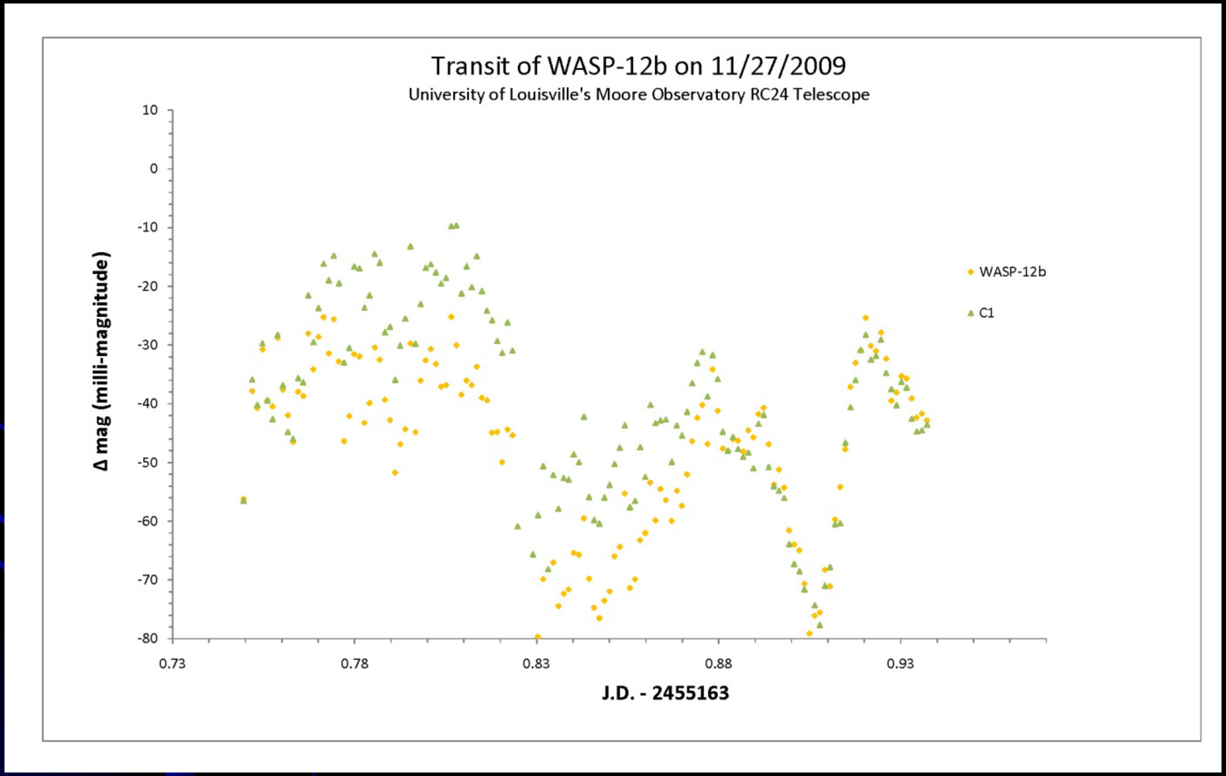
Differential Aperture Photometry

- Identify comparisons of similar brightness (and spectral type if possible)
- Perform aperture photometry on each of the comparison stars
- Ensure that the comparison stars are not varying above noise levels with respect to each other



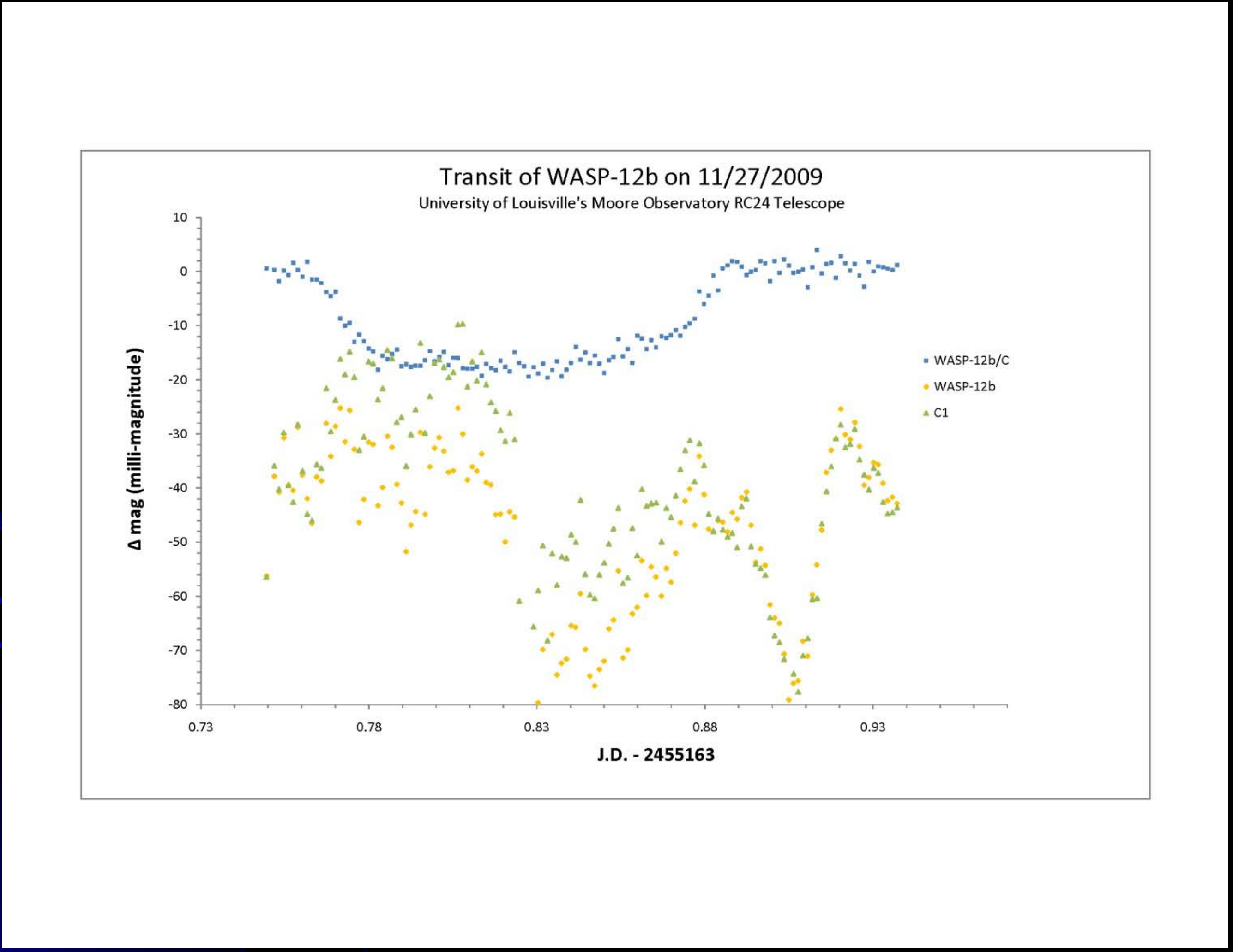
Differential Photometry

- Integrated net comparison star counts in green
- Integrated net target star counts in yellow
- Obvious atmospheric effects, but starting to see something interesting



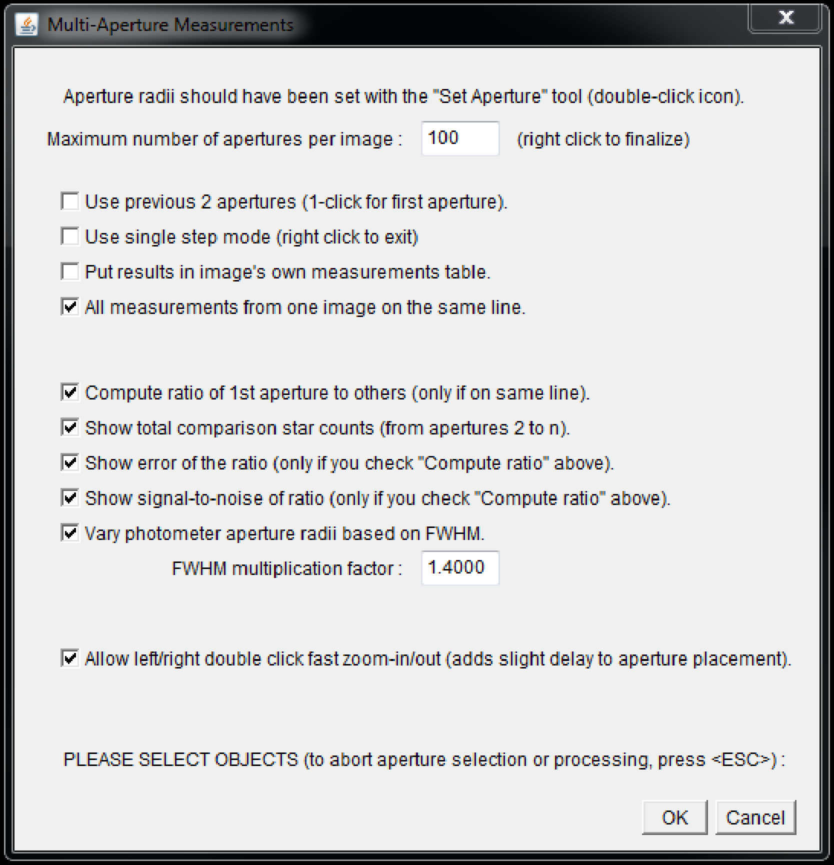
Differential Photometry

- Take the ratio of the target to comparison star integrated counts
- Even Louisville's atmospheric effects are essentially eliminated!



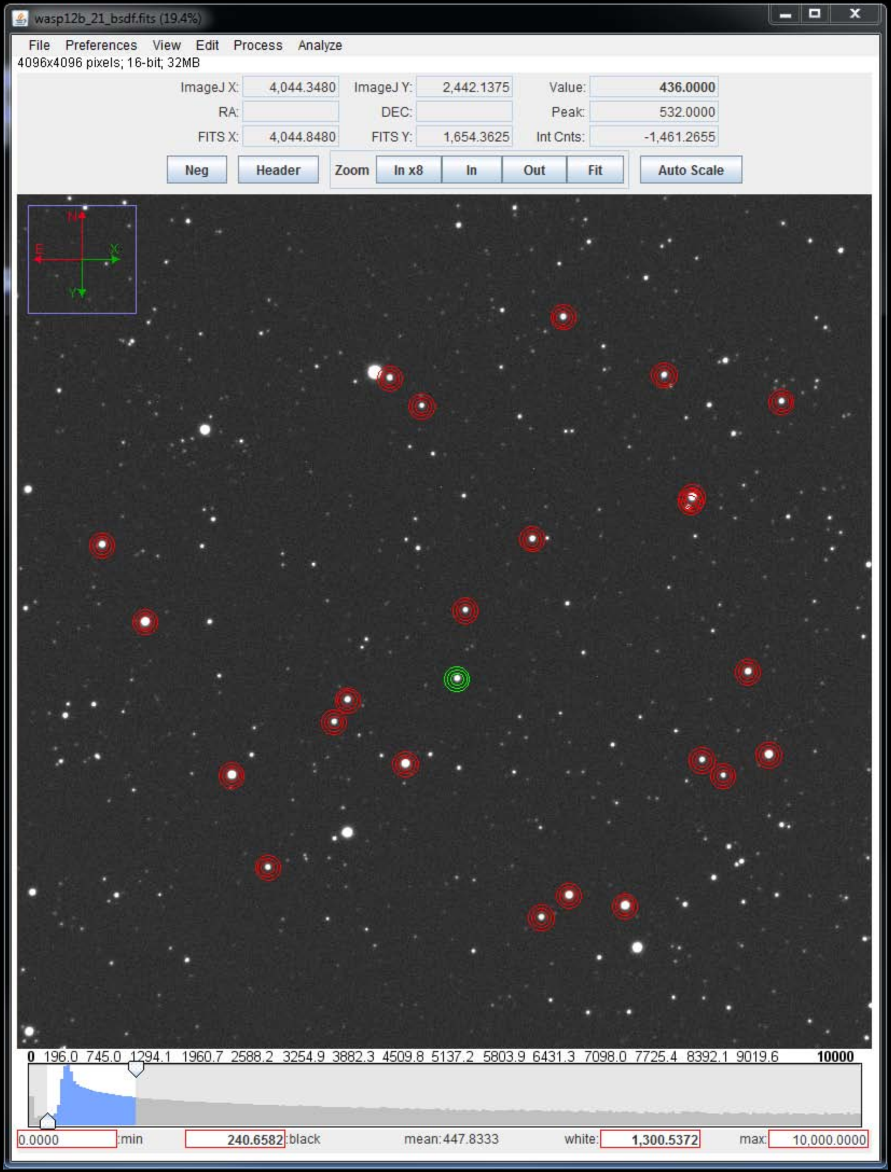
Multi-Aperture Module

- AstroIJ’s differential photometry setup module
- Allows any number of comparison stars
- Calculates ratio and error of the ratio
- Has option of using variable photometer radii based on average FWHM in each image
  - Works very well for our highly varying Louisville skies



Multi-Aperture Module

- In first exposure, click near the target star (green) and then each of the comparison stars (red)
- Each aperture is placed at centroid of star
- Image sequence is processed automatically
- Apertures placed at new centroid locations in each image
- New feature planned to select stars automatically with post processing to select optimum set (see Broeg et al. 2005)



Photometric Results

Measurements

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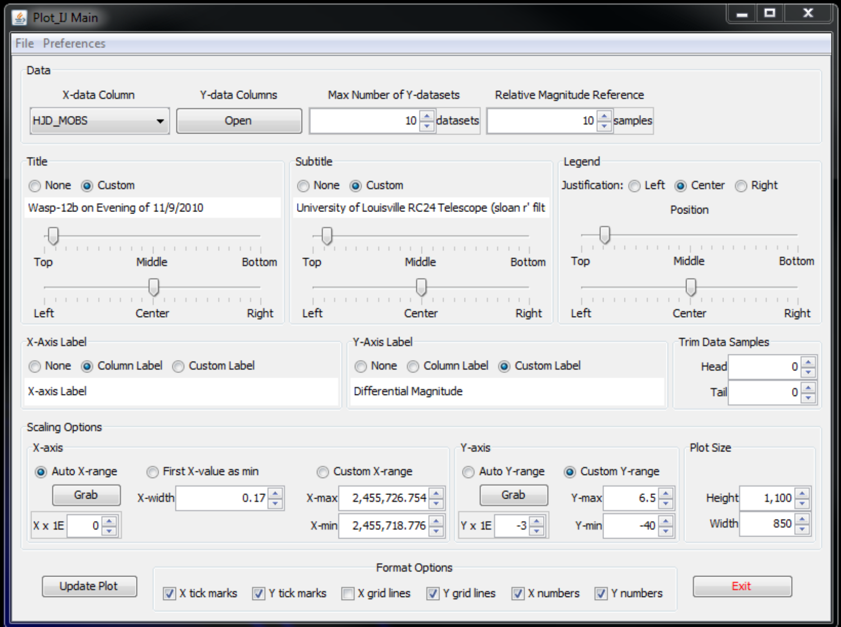
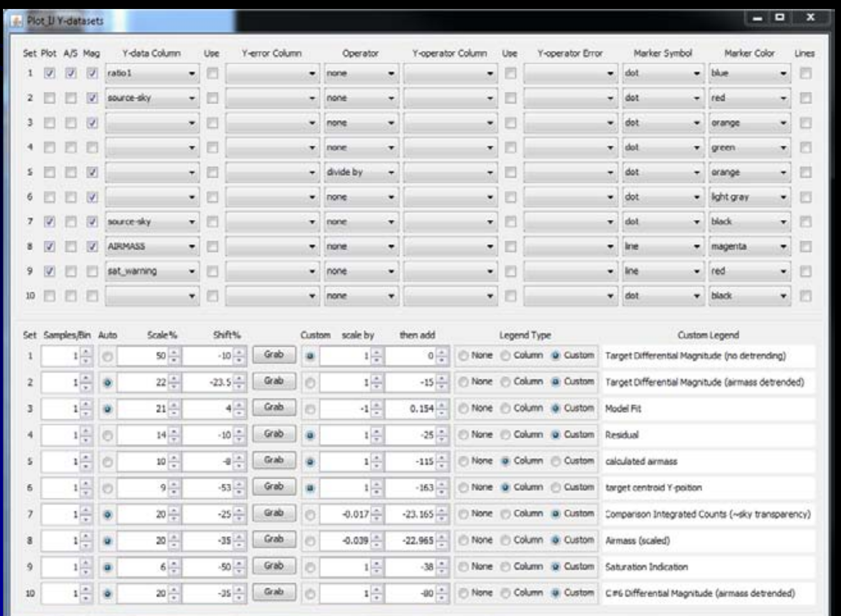
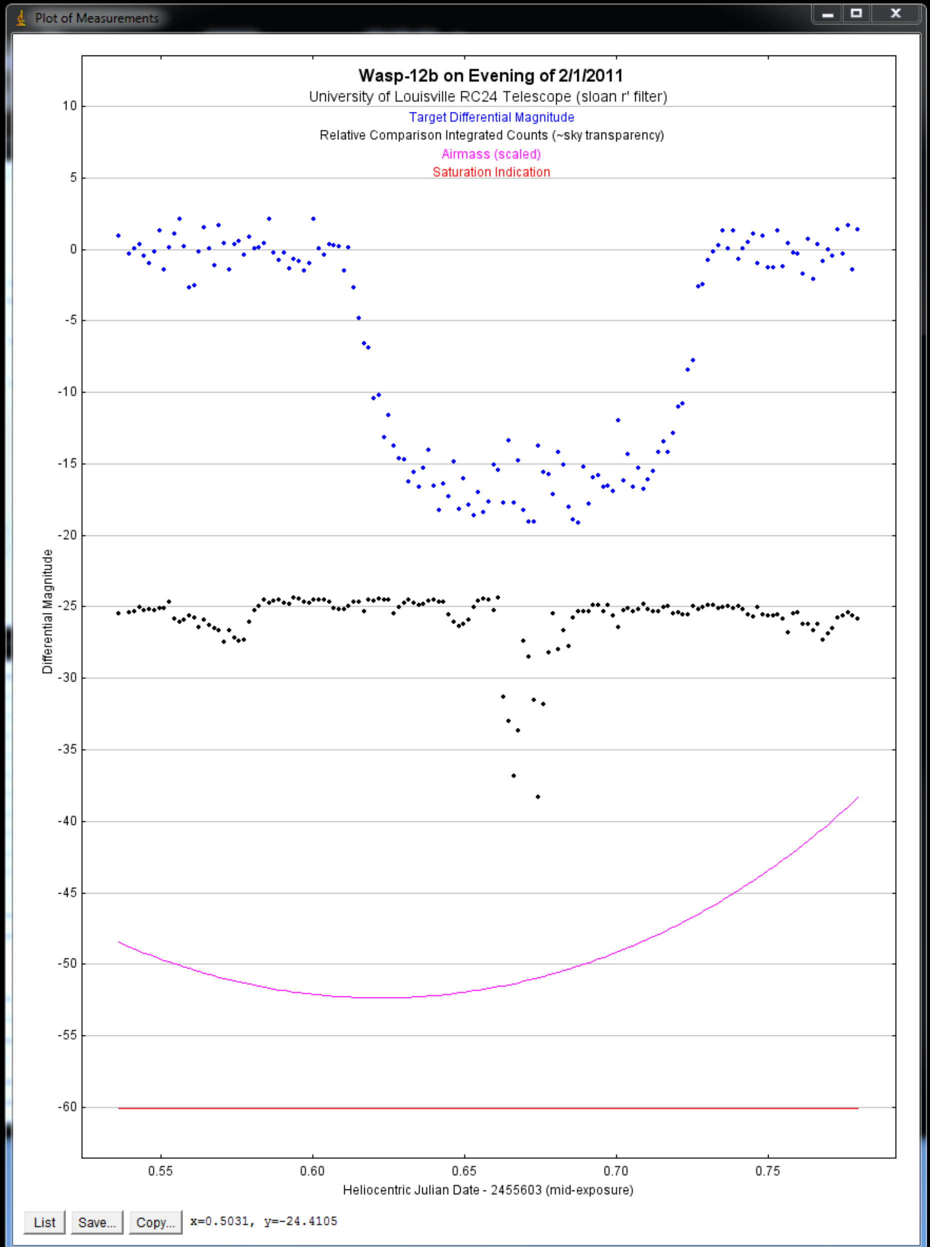
	image	slice	x	y	source-sky	peak	sat_warning	source_error	sky/pixel	J.D.-2400000	JD_SOBS	JD_MOBS	HJD_MOBS
1	wasp12b_21_bsdf.fits	1	2109.198415	1776.836068	1805465.670490	11447	0	1908.876176	444.485664	55603.532188	2455603.531493	2455603.532188	2455603.536238
2	wasp12b_22_bsdf.fits	2	2104.826086	1774.118519	1809193.246314	12978	0	1915.351623	453.095403	55603.535752	2455603.535058	2455603.535752	2455603.539803
3	wasp12b_23_bsdf.fits	3	2108.158419	1770.332503	1817817.419955	13229	0	1937.933025	465.563719	55603.537419	2455603.536725	2455603.537419	2455603.541470
4	wasp12b_24_bsdf.fits	4	2105.242512	1767.119908	1840593.981366	16361	0	1926.550710	452.406832	55603.539062	2455603.538368	2455603.539062	2455603.543113
5	wasp12b_25_bsdf.fits	5	2108.596253	1767.809303	1826938.978388	14536	0	1921.854594	448.470959	55603.540706	2455603.540012	2455603.540706	2455603.544756
6	wasp12b_26_bsdf.fits	6	2105.763600	1771.117576	1827334.817637	16299	0	1916.528359	453.500856	55603.542350	2455603.541655	2455603.542350	2455603.546400
7	wasp12b_27_bsdf.fits	7	2107.550136	1775.683152	1825524.041741	14028	0	1918.486710	448.238899	55603.543993	2455603.543299	2455603.543993	2455603.548043
8	wasp12b_28_bsdf.fits	8	2107.516286	1775.300721	1838165.456156	15055	0	1929.210261	450.174920	55603.545637	2455603.544942	2455603.545637	2455603.549687
9	wasp12b_29_bsdf.fits	9	2108.786452	1775.263058	1836828.683164	12242	0	1922.046374	448.897923	55603.547280	2455603.546586	2455603.547280	2455603.551330
10	wasp12b_30_bsdf.fits	10	2106.202669	1776.077656	1875817.639896	21596	0	1925.979284	446.650259	55603.548924	2455603.548229	2455603.548924	2455603.552973
11	wasp12b_31_bsdf.fits	11	2106.986544	1773.849094	1777910.964717	16694	0	1955.211209	485.510678	55603.550567	2455603.549873	2455603.550567	2455603.554617
12	wasp12b_32_bsdf.fits	12	2107.173437	1774.720896	1758095.159149	11586	0	1932.607708	492.456596	55603.552222	2455603.551528	2455603.552222	2455603.556272
13	wasp12b_33_bsdf.fits	13	2107.447149	1774.883476	1771208.503759	13623	0	1936.380867	482.796992	55603.553866	2455603.553171	2455603.553866	2455603.557915
14	wasp12b_34_bsdf.fits	14	2107.354859	1774.071393	1795863.010619	20201	0	1949.467440	489.828319	55603.555509	2455603.554815	2455603.555509	2455603.559559
15	wasp12b_35_bsdf.fits	15	2106.878614	1775.473660	1779503.694575	16248	0	1931.467765	485.949594	55603.557141	2455603.556447	2455603.557141	2455603.561190
16	wasp12b_36_bsdf.fits	16	2108.188685	1774.752560	1729979.176471	16473	0	1945.162916	504.029412	55603.558785	2455603.558090	2455603.558785	2455603.562834
17	wasp12b_37_bsdf.fits	17	2106.325666	1775.531173	1770944.797147	17069	0	1958.129149	503.874276	55603.560440	2455603.559745	2455603.560440	2455603.564489
18	wasp12b_38_bsdf.fits	18	2106.967760	1774.307941	1738051.458740	17563	0	1969.860362	526.222272	55603.562083	2455603.561389	2455603.562083	2455603.566132
19	wasp12b_39_bsdf.fits	19	2107.719483	1774.803880	1724385.523973	16429	0	1958.013015	526.815925	55603.563727	2455603.563032	2455603.563727	2455603.567776
20	wasp12b_40_bsdf.fits	20	2107.500433	1775.273924	1707630.636528	15993	0	1980.422252	541.466546	55603.565370	2455603.564676	2455603.565370	2455603.569419
21	wasp12b_41_bsdf.fits	21	2108.824927	1776.491611	1649703.925110	18271	0	2007.067823	593.136564	55603.567014	2455603.566319	2455603.567014	2455603.571062
22	wasp12b_42_bsdf.fits	22	2104.818575	1774.124859	1711167.612272	16834	0	1977.108068	546.251088	55603.568657	2455603.567963	2455603.568657	2455603.572706
23	wasp12b_43_bsdf.fits	23	2108.352042	1774.003509	1671612.997416	19285	0	1991.236611	578.319552	55603.570301	2455603.569606	2455603.570301	2455603.574349
24	wasp12b_44_bsdf.fits	24	2107.436162	1775.283451	1652550.802683	19070	0	2003.648164	593.964950	55603.571944	2455603.571250	2455603.571944	2455603.575993
25	wasp12b_45_bsdf.fits	25	2107.794972	1775.850630	1659107.039846	16774	0	1994.139449	583.639674	55603.573588	2455603.572894	2455603.573588	2455603.577636
26	wasp12b_46_bsdf.fits	26	2104.823302	1775.136596	1756646.298836	18398	0	1963.960166	521.975420	55603.575231	2455603.574537	2455603.575231	2455603.579279
27	wasp12b_47_bsdf.fits	27	2107.153124	1775.266702	1821654.989091	18662	0	1944.214649	470.932727	55603.576875	2455603.576181	2455603.576875	2455603.580923
28	wasp12b_48_bsdf.fits	28	2107.413574	1775.931638	1846483.531933	23509	0	1928.612835	462.671667	55603.578519	2455603.577824	2455603.578519	2455603.582566
29	wasp12b_49_bsdf.fits	29	2107.175956	1774.148408	1885329.025896	20023	0	1915.471364	434.511437	55603.580162	2455603.579468	2455603.580162	2455603.584210
30	wasp12b_50_bsdf.fits	30	2107.326827	1775.856567	1870136.341900	15306	0	1923.934132	434.135842	55603.581806	2455603.581111	2455603.581806	2455603.585853
31	wasp12b_51_bsdf.fits	31	2104.871004	1772.937822	1879049.290407	19296	0	1917.620505	432.959264	55603.583449	2455603.582755	2455603.583449	2455603.587496
32	wasp12b_52_bsdf.fits	32	2107.952676	1776.506051	1885989.759693	20120	0	1913.064170	436.865360	55603.585093	2455603.584398	2455603.585093	2455603.589140
33	wasp12b_53_bsdf.fits	33	2104.010000	1775.033264	1868031.934727	20808	0	1934.310062	458.927048	55603.586736	2455603.586042	2455603.586736	2455603.590783
34	wasp12b_54_bsdf.fits	34	2107.316283	1776.060548	1864325.975904	22896	0	1919.754510	446.632530	55603.588391	2455603.587697	2455603.588391	2455603.592438
35	wasp12b_55_bsdf.fits	35	2106.166229	1775.092409	1902712.221140	24871	0	1936.888717	434.208623	55603.590035	2455603.589340	2455603.590035	2455603.594081
36	wasp12b_56_bsdf.fits	36	2107.024732	1775.734059	1890770.643911	21365	0	1932.658449	436.066882	55603.591678	2455603.590984	2455603.591678	2455603.595725
37	wasp12b_57_bsdf.fits	37	2106.230839	1774.327912	1872538.681508	19730	0	1931.063405	442.850977	55603.593322	2455603.592627	2455603.593322	2455603.597368
38	wasp12b_58_bsdf.fits	38	2107.431410	1775.203529	1868230.124174	23122	0	1928.471769	449.417878	55603.594965	2455603.594271	2455603.594965	2455603.599012
39	wasp12b_59_bsdf.fits	39	2107.257992	1776.431654	1889607.880584	21447	0	1931.190690	444.290137	55603.596609	2455603.595914	2455603.596609	2455603.600655
40	wasp12b_60_bsdf.fits	40	2106.032342	1775.232603	1886953.659253	18187	0	1929.510584	441.534253	55603.598252	2455603.597558	2455603.598252	2455603.602298
41	wasp12b_61_bsdf.fits	41	2105.289110	1773.639413	1884658.180692	27718	0	1926.567660	449.188808	55603.599896	2455603.599201	2455603.599896	2455603.603942

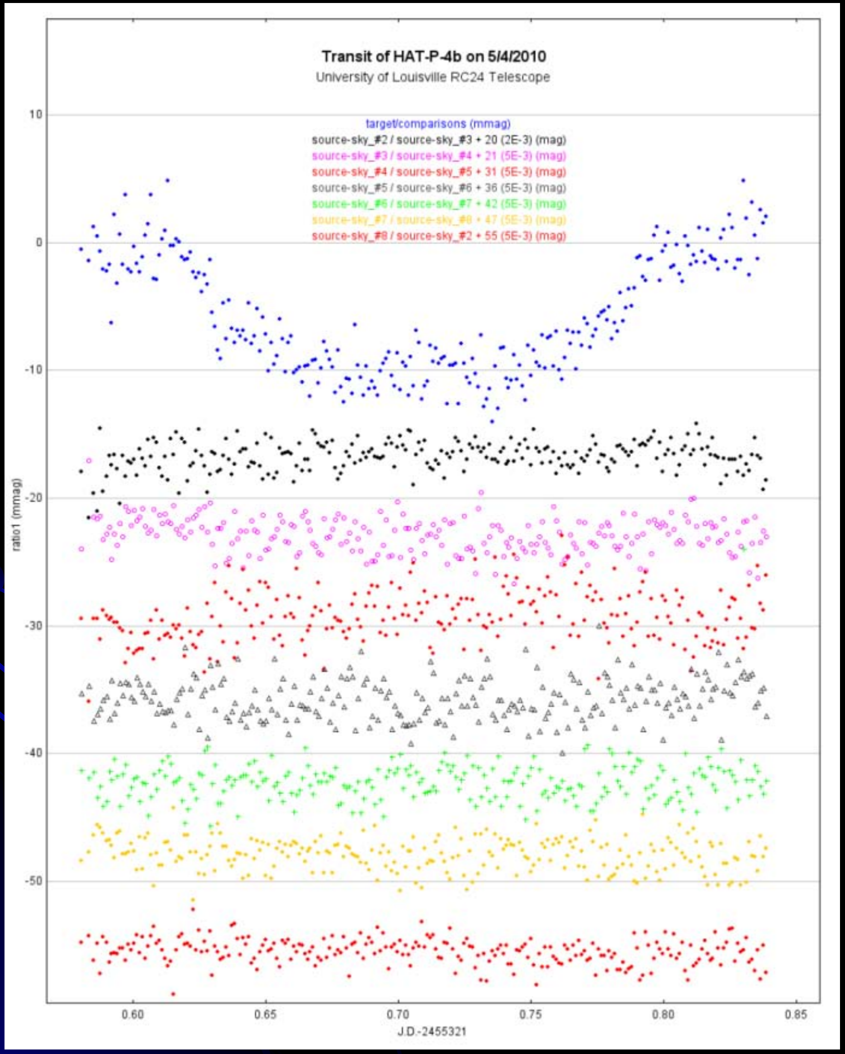
Plotting Facility







Easy to Assess Suitability of Comparison Stars



(We plan to automate comparison star assessment and selection in the future)

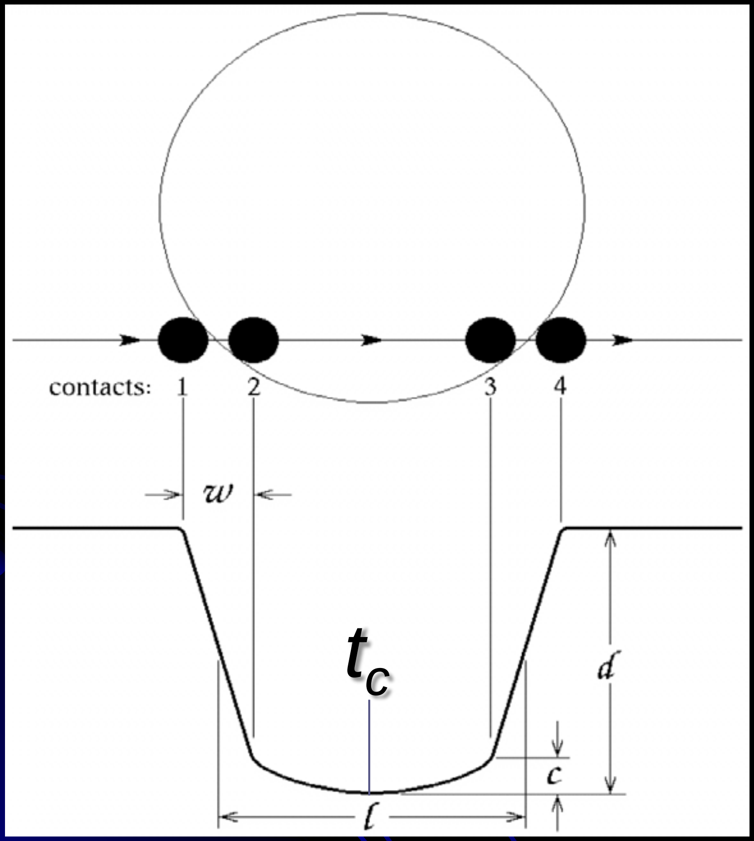
Transits Observed with RC24

- In the process of proving in our instrumentation and developing software we have observed 60 transits since late 2009
- >60 total transits observed
- 12 with >1 epoch observed
- 20 follow-up observations for wide-field transit surveys

Planet	Transits
HAT-P-3b	1
HAT-P-4b	1
HAT-P-4b	1
HAT-P-4b	1
HAT-P-10b	1
HAT-P-11b	4
HAT-P-13b	1
HAT-P-14b	2
HAT-P-16b	3
HAT-P-19b	1
HAT-P-20b	1
HAT-P-21b	1
HAT-P-23b	2
HAT-P-27b	1
Qatar-1b	2
HD 149026b	1
CoRoT-7b	1

Planet	Transits
Kepler 8b	1
TrES-2b	1
TrES-3b	1
WASP-1b	4
WASP-2b	2
WASP-12b	7
WASP-24b	1
WASP-28b	1
WASP-33b	5
WASP-37b	1
WASP-38b	1
XO-1b	1
XO-3b	4
XO-4b	2
HD 189733b	2
HD 209458b	1
GJ-436	1

Transit Observables



d = depth of transit
➡ *planet to star radius ratio*

ℓ = duration of transit and
w = duration of ingress/egress
➡ *~impact angle*

t_c = time of transit center
➡ *exoplanet orbital period*

c ➡ *stellar limb darkening coefficients*

t_c periodicity variations
➡ unseen *perturbing exoplanets*

Transit Model Parameters

- Fit a parameterized model to the photometric data.
- Model parameters
  - Planet radius, R_p
  - Semi-major axis, a
  - Inclination, i
  - Epoch of the transit center time, t_c
  - Orbital period, P
  - Eccentricity arguments, e and ω
  - Limb darkening coefficients, γ_1, γ_2 (†)
  - Stellar radius, R_* (††)
  - Stellar mass, M_* (††)
  - Planet mass, M_p (†††)

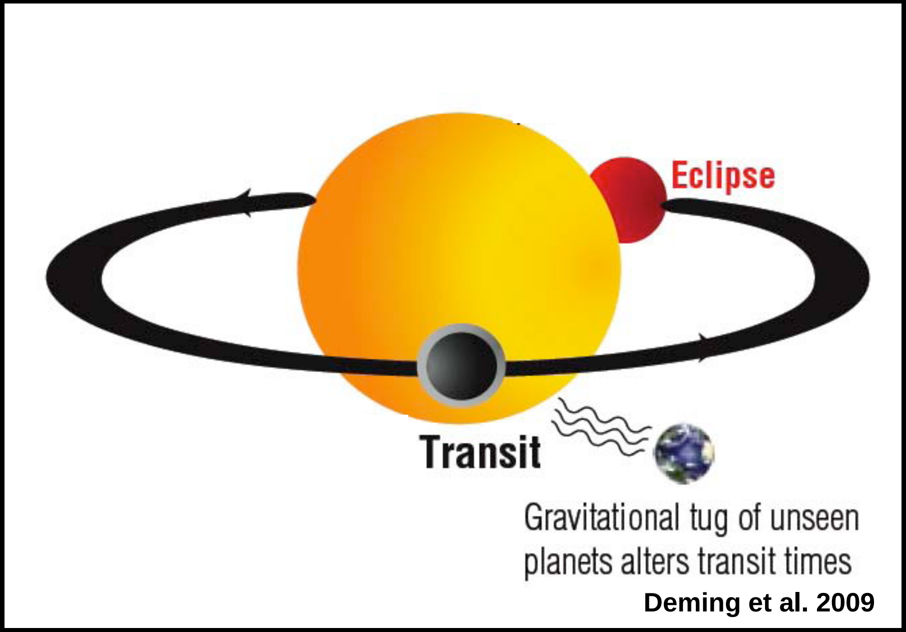
(†) for ground based photometry, usually estimated from log$g$, T_{eff}, and theoretical limb darkening tables
(††) estimated from spectral type, luminosity, and stellar model isochrones
(†††) the planetary mass M_P is irrelevant to the model except for its small effect on the relation between P and the semi-major axis

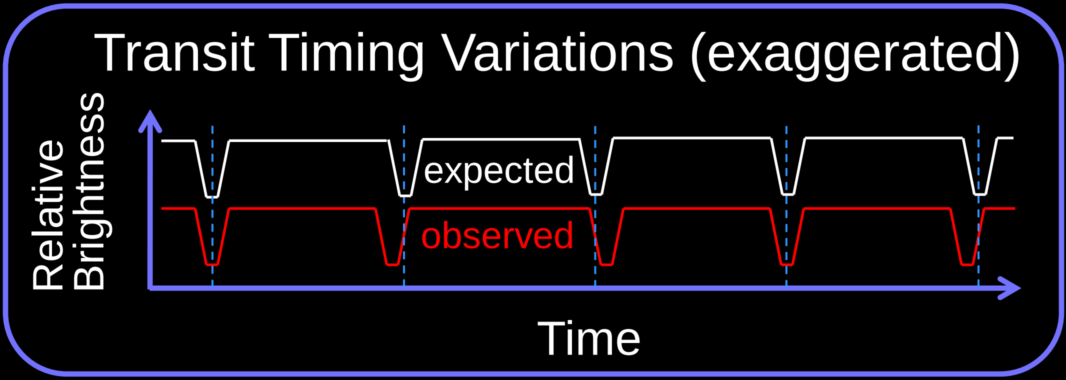
Light Curve Modeling Tools

- Exoplanet Transit Database (ETD) is nice for quick look modeling
- We have traditionally used JKTEBOP (Southworth 2008)
  - Best fit from Levenberg-Marquardt optimization algorithm
  - Parameter error estimates using Monte Carlo or residual permutation (prayer bead)
- Transit Analysis Package (TAP) offers different approach (Gazak et al.)
  - Uses Markov Chain Monte Carlo (MCMC) and Bayesian inference to estimate model parameters and parameter errors
  - Uses wavelet decomposition techniques of Carter & Winn 2009 to handle the effects of correlated noise
- We plan to integrate modeling into AstroImageJ

Transit Timing Variations (TTVs)

- Undetected planet tugs on its star and the known transiting planet
- As a result, the known planet's transit center time is slightly perturbed
- Planets in mean motion resonance can create particularly large TTVs which should be detectable from the ground





Ground Based TTV Detection Practicalities

- Many full transit observations are required per exoplanet
- Special care must be taken with timing accuracy (i.e. BJD_{TDB}) (see Eastman et al. 2010)
- Veras et al. 2011 argue that at least 50 consecutive transits are required to characterize the mass and orbital parameters of a perturber
- Garcia-Melendo & Lopez-Morales 2011 propose that ground based surveys may be discarding systems with large TTV
  - Ground based surveys use Box-fitting Least Squares (BLS) based algorithms
  - Large TTVs will cause BLS to discard planet
  - Kepler data suggests that out of the (non-Kepler field) known hot Jupiters ~7 systems with significant TTV's should exist
  - No ground-based TTV detections have been confirmed to date

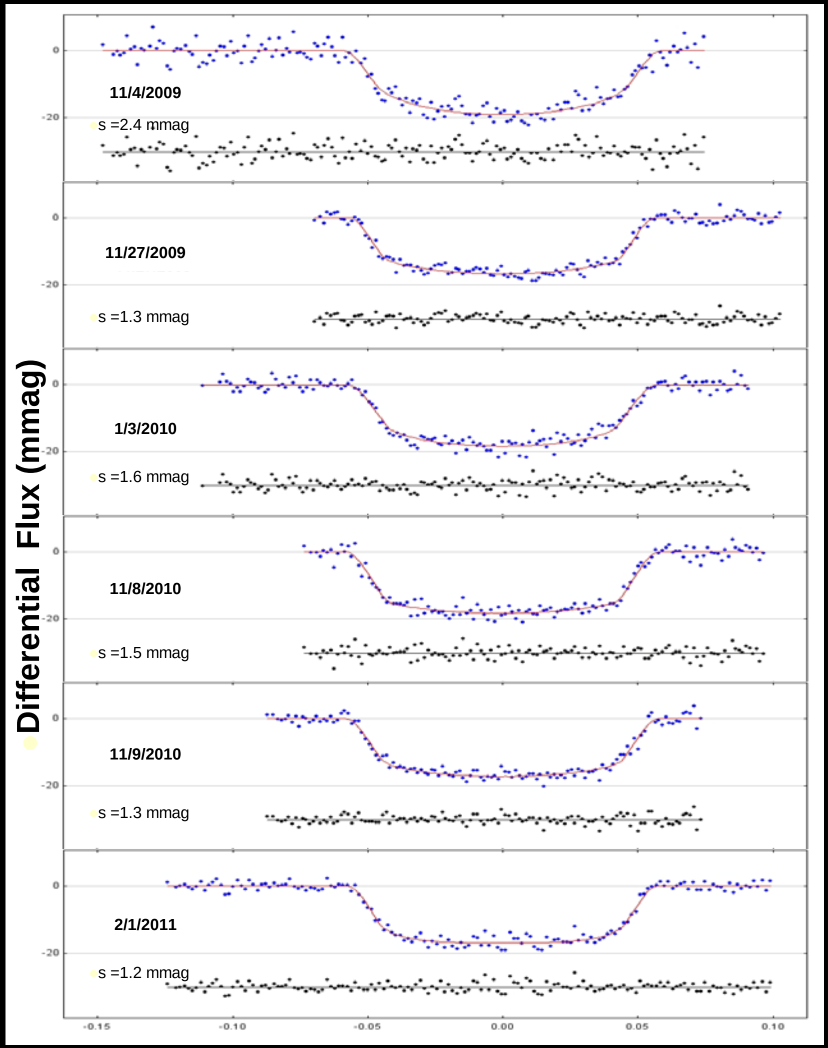
Should we Continue Ground-based TTV Work?

- Long period TTVs can be detected with sparse ground sampling
- Any detection of TTVs can set lower limits for TTV amplitude and possibly justify further radial velocity studies
- Maybe GM & LM 2011 over-estimate BLS's rejection rate
  - I count only about 10 out of 100 systems with reported TTV studies in the literature
  - Some of those studies report only 2-3 epochs of data
- And if not, BLS algorithms will likely be improved
- As a side benefit, a longer time base of observations yields more precise system parameters

Some Early TTV Analysis Results

- Six transit epochs analyzed (7th with poor pre-ingress data needs further analysis)
- Blue dots are the airmass detrended photometry
- Red line is the best fit JKTEBOP model
- The black dots are the model residuals shifted by 30 mmag for clarity.

WASP-12b Transits
(UofL Moore observatory RC24 telescope)



Orbital Phase

Observed – Calculated Residuals

- 6 UofL RC24 data sets plus 6 from the literature
- Literature data are from 2 meter class telescopes at typical observatory altitudes
- All data modeled/ re-modeled using JKTEBOP with same free parameters
- O-C calculated using least squares best fit constant orbital period of P=1.09142143 days

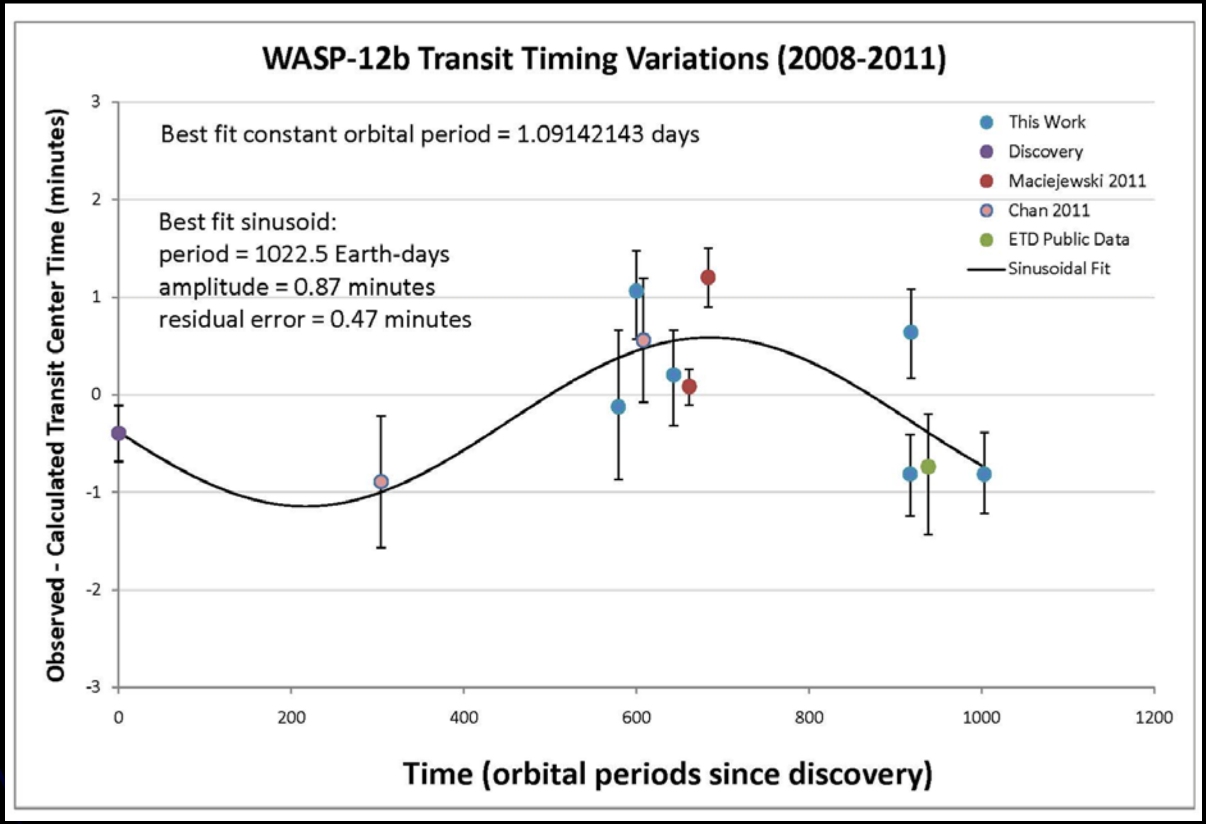
WASP-12b O-C Data

(UofL Moore observatory RC24 observations + literature)

Observation Date	Observation Source	Epoch	Transit Center Time (BJD_{TDB})	TTV O-C (minutes)	$(R_p/R_*)^2$ (x1000)	Residual (mmag)
02/18/2008	Hebb '09	0	2454508.976866	-0.396	13.8	n/a
01/08/2009	Chan '11	304	2454840.768603	-0.892	12.5	1.8
11/04/2009	This Work	579	2455140.910078	-0.123	13.3	2.4
11/27/2009	This Work	600	2455163.830826	1.062	13.0	1.3
12/06/2009	Chan '11	608	2455172.561816	0.559	12.5	1.1
01/13/2010	This Work	643	2455210.761295	0.202	14.4	1.6
02/02/2010	Mac 2011	661	2455230.406791	0.083	14.3	0.6
02/26/2010	Mac 2011	683	2455254.418911	1.203	14.0	1.0
11/08/2010	This Work	917	2455509.809995	-0.815	15.1	1.5
11/09/2010	This Work	918	2455510.902520	0.640	13.7	1.3
12/01/2010	ETD	938	2455532.729903	-0.739	11.3	1.4
02/01/2011	This Work	1003	2455603.672237	-0.816	13.2	1.2

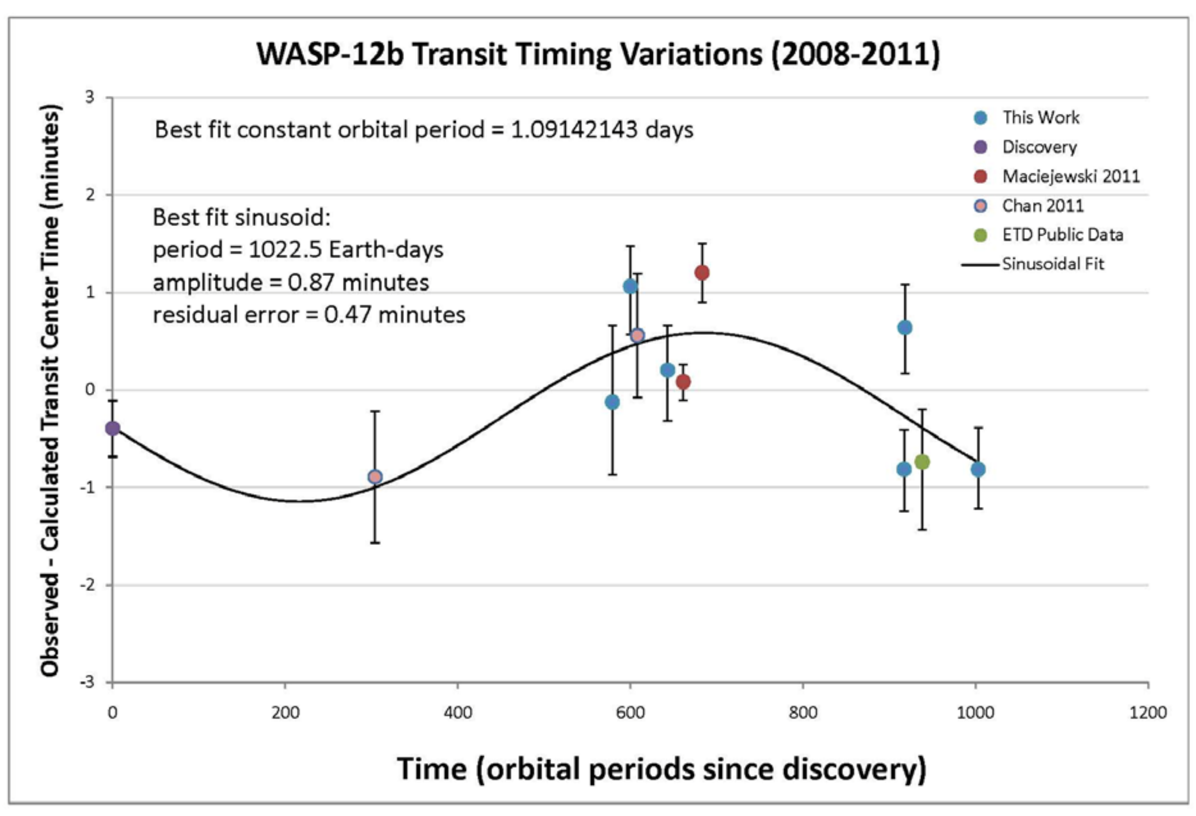
Observed – Calculated Residuals

- The O-C residuals below were determined using the least squares best fit constant orbital period of P=1.09142143
- Best fit low frequency sinusoid to the residuals has a period of 1022.5 days and an amplitude of 0.87 minutes
- Using "Mercury" N-body simulation code (Chambers 1999) to investigate possible perturber phase space



Observed – Calculated Residuals

- Object in 1022.5 day orbit would be stellar in mass
- Searching MMR space next
- Orbital fits are degenerate…
- Need more data to increase confidence in constant + sinusoidal solution
- Observable again in October



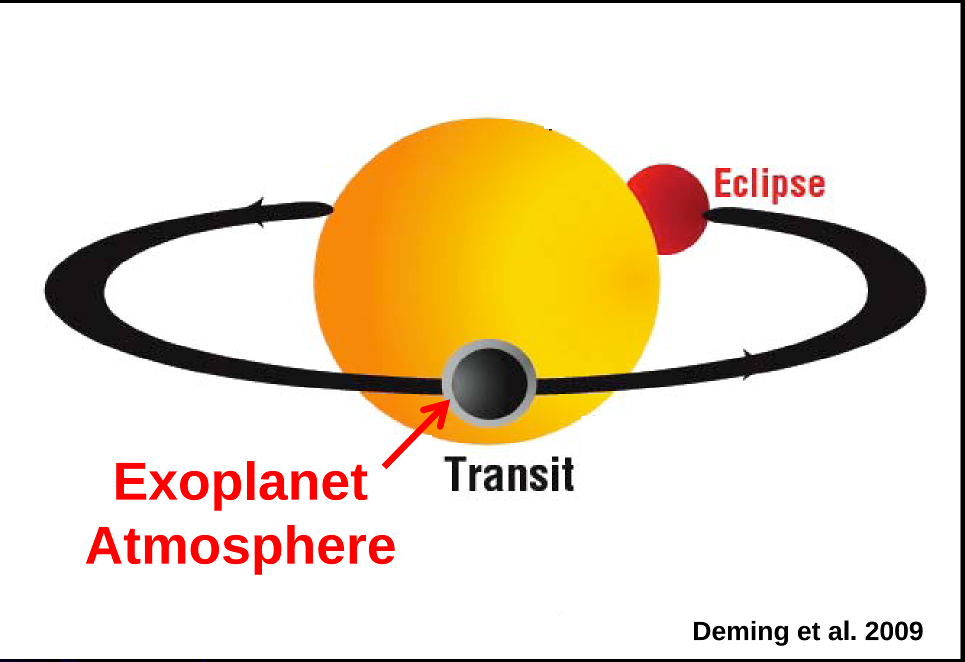
Atmospheric Detection

- An additional goal is to detect atmospheres of exoplanets in the optical
  --- with a 60 cm telescope!

- If we can do it for bright host stars, maybe the method could be extended to larger aperture telescopes for dimmer objects

Transmission Spectroscopy Geometric Configuration

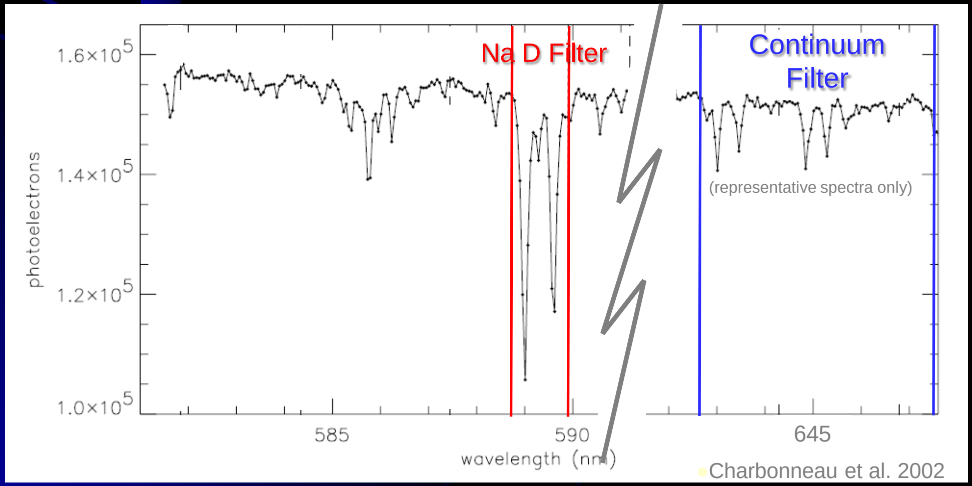
- During transit, part of the stellar light passes through the atmosphere of the exoplanet
- Using spectroscopy or narrowband imaging, components of the exoplanet's atmosphere can be measured



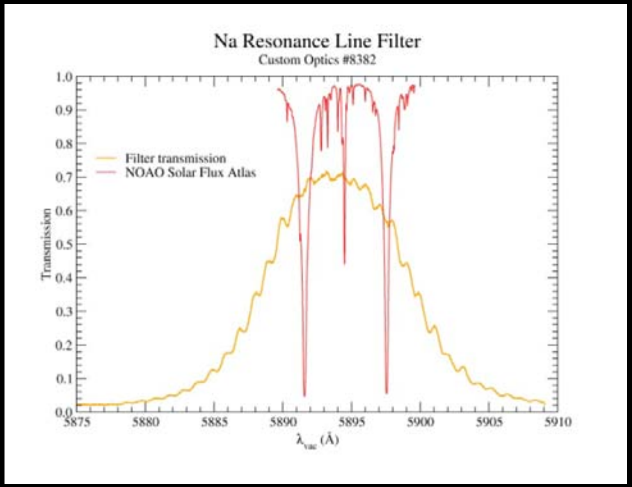
Detecting the Atmosphere

- Initial focus is on Na D 590 nm doublet
  - atmospheric absorption is expected to be strong (Seager & Sasselov 2000)
- Using high efficiency narrow-band filters
  - λ_c = 589.5 nm, 1 nm width for Na D doublet
  - λ_c = 645.0 nm, 5 nm width for continuum
- Alternate filters between successive exposures
- Filters automatically changed during 20 sec CCD readout
- Compare transit depths in two filters

Spectrum Near Na D 590 nm Doublet

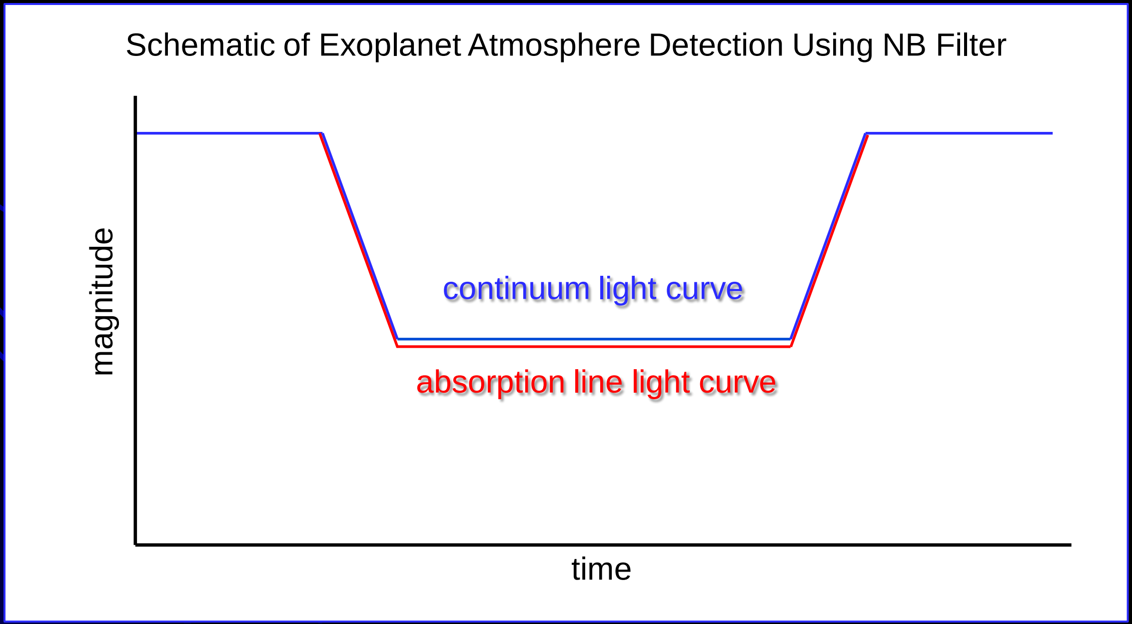


Actual Na D Filter Performance



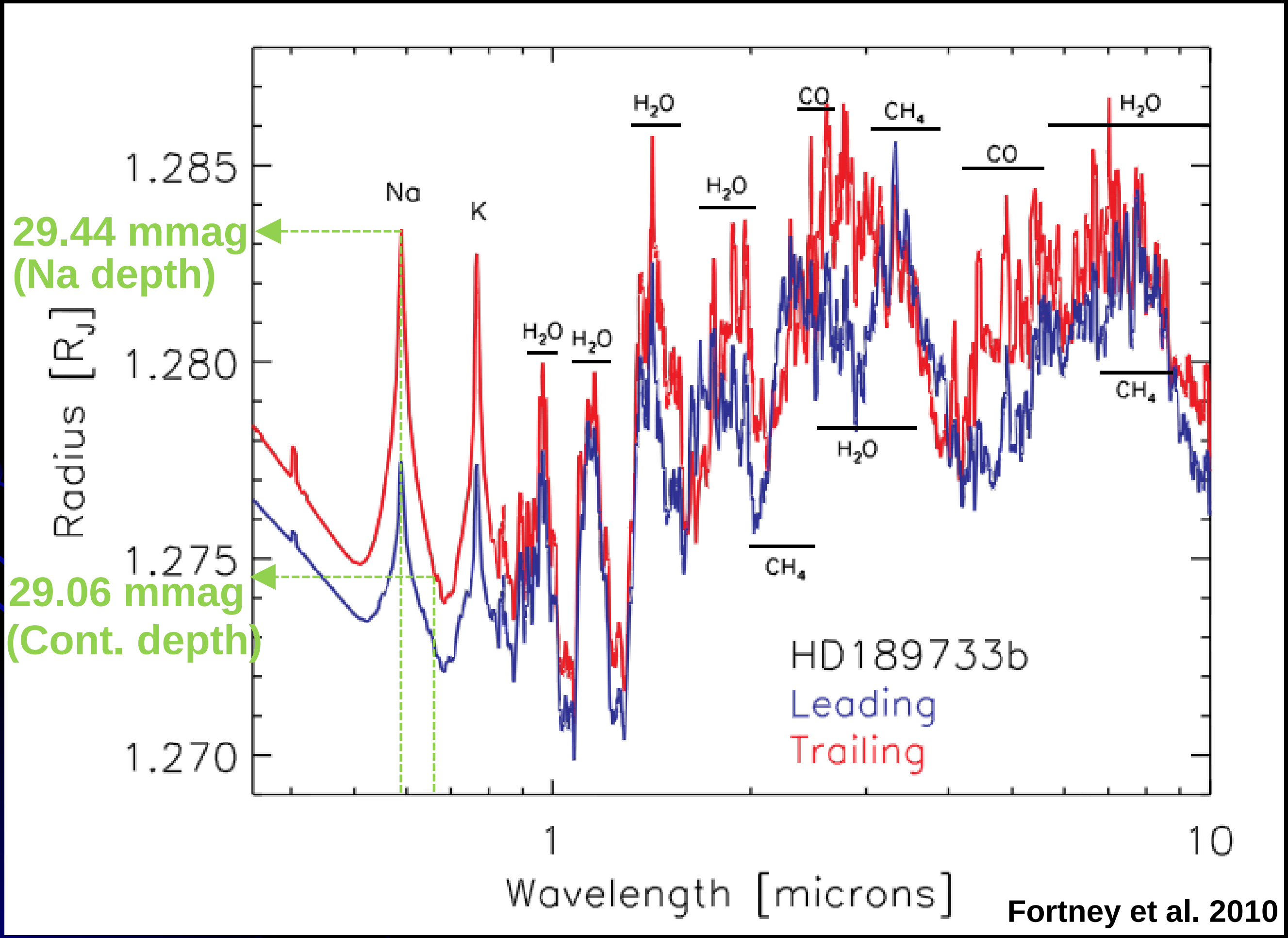
Light Curve Signature

- When an atmospheric absorption line is detected, the planet will appear “larger” in the absorption line than in the continuum
- Expect absorption line transit depth to be slightly increased compared to the continuum depth
- Sing et al. 2010 have recently demonstrated the concept
  - using the GTC 10.4 m telescope
  - tunable Fabry-Perot etalon set to a width of 1.2 nm
  - 4-σ detection of potassium in atmosphere of XO-2b



HD 189733b Model Spectra

- Fortney et al. 2010 HD 189733b model transmission spectra (in terms of planet radius)
- Predicted $\mathrm{Depth}_{\mathrm{Na\ D}} - \mathrm{Depth}_{\mathrm{continuum}} = 0.38$ mmag



Signal-to-Noise Requirement

- Planet atmosphere to stellar disk size ratio is $\sim 10^{-4}$
- HD 189733b has measured <u>excess</u> Na D absorption of 0.67 mmag. (11 transits from 9.2 m telescope - Redfield et al. 2008)
- For a 3σ detection, we need a depth precision of ~ 0.2 mmag

First RC24 Narrowband Observations

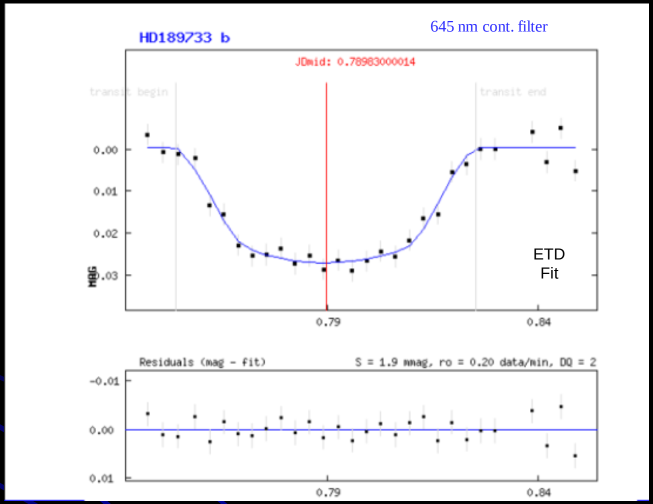
- HD 189733 was observed with RC24 on 7/11/2011
- Transit bracketed by clouds => poor out-of-transit coverage
- 5 nm wide continuum filter – 40 sec exposures
- 1 nm wide Na D filter – 200 sec exposures
- Alternating filters each exposure

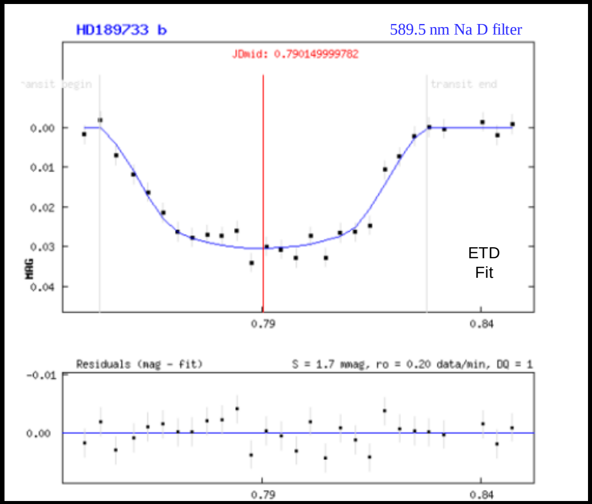
First RC24 Narrowband Observations

- Quick fit using ETD shows depth & duration difference

645 nm continuum
depth = 27.2 ± 1.1 mmag
duration = 107.6 ± 2.3 min

589.5 nm Na D
depth = 30.3 ± 1.1 mmag
duration = 102.1 ± 2.4 min

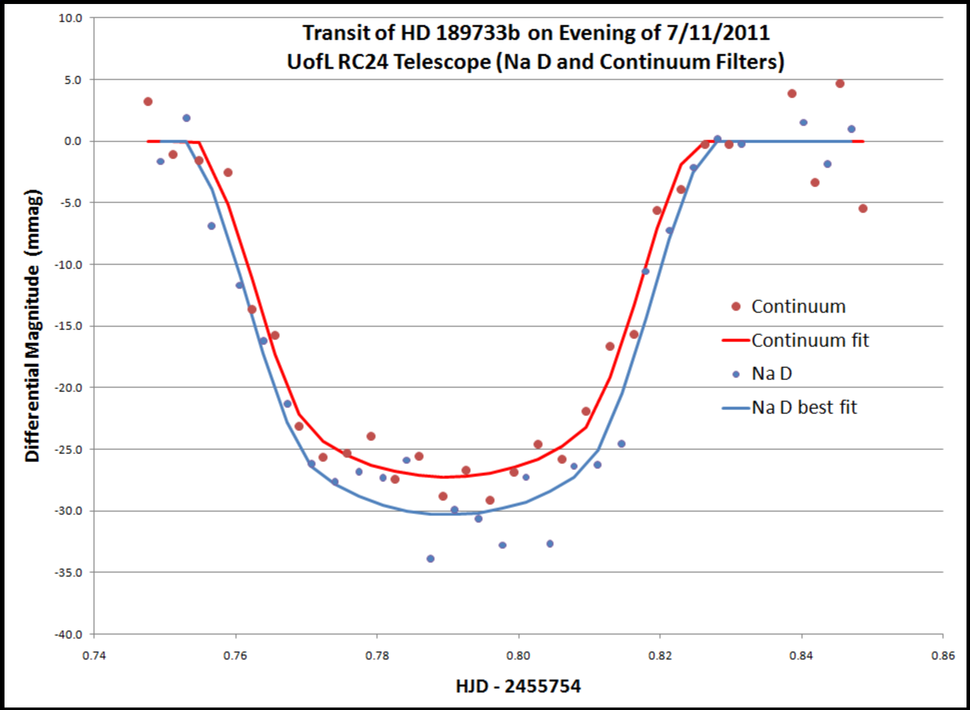




  - poor per exposure error due to light clouds
  - poor depth error bars due to lack of OOT signal
  - expected 0.5 mmag depth error for HD 189733b will <u>require 6-8 transits</u> for firm 3-σ detection

First RC24 Narrowband Observations

- Δdepth=3.1±1.6 mmag, Δduration=5.5±3.2 min, Δt_c=28±61 sec
- Compare to 0.38 mmag prediction by Fortney model spectra and 0.67 mmag Redfield measurement
- Possibly due to insufficient OOT data resulting in:
  - detrending inaccuracies
  - modeling inaccuracies
- At least the difference is in the correct direction
- The t_c times are within error bars
- More observations required!



Atmospheric Observing Plan

- Continue HD 189733b observations
- Start HD 209458 observations now (should also require ~6 transits for 3-σ detection)
- Assess feasibility of other systems as above data comes in

Roadmap

- Bring 3 additional telescopes up to same level of performance as RC24
- Continue atmospheric observations
- Continue TTV observations when no atmospheric targets are available
- Complete full analysis on combined datasets as they become available
- Continue photometric follow-up for wide-field surveys
- Continue AstroImageJ development
  - Light curve detrend + modeling
  - TTV residual analysis + plotting
  - Multi-aperture optimal selection of targets

Additional References

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