Lecture 9

November 1, 2018

Lab 5 Analysis

News

- Lab 2
  - Handed back with solution; mean: 92.1, std dev: 5.5
- Lab 3
  - Handed back next week (I hope).
- Lab 4
  - Due November 1 (today)

News

- Lab 5 (Transiting Exoplanets)
  - Observing completed, start working on analysis.
    - Monday, Tuesday, and Wednesday groups use the data that you obtained (unless you hear from me otherwise).
    - Friday and Sunday groups use data that I will assign you (tonight, I hope).
  - Due November 8

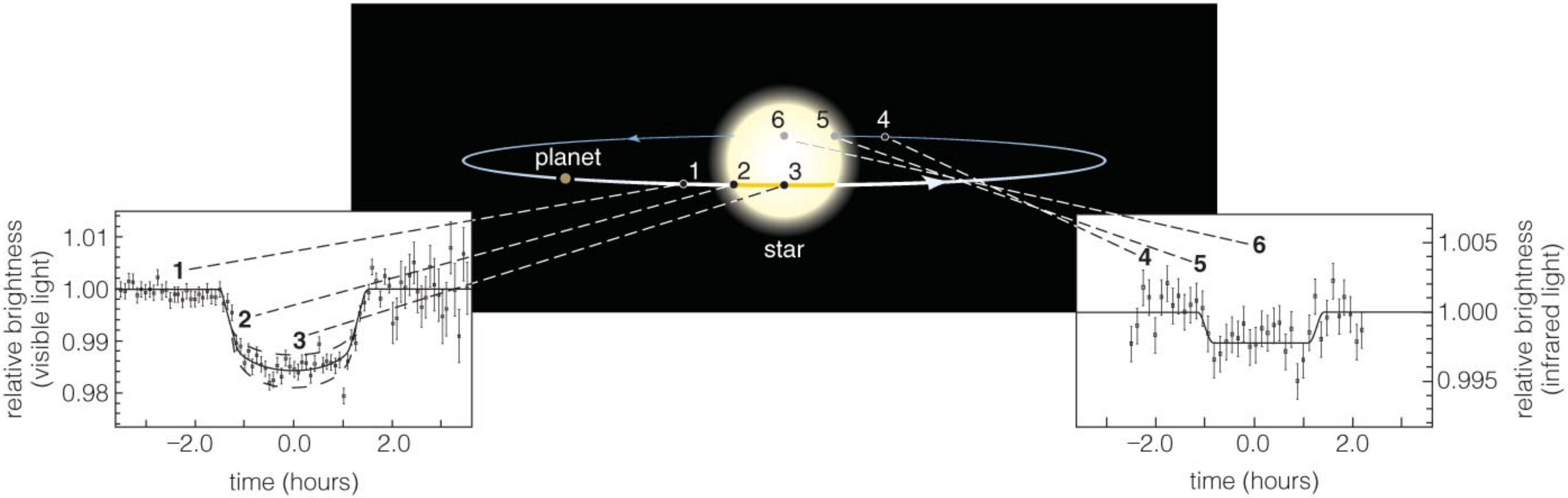
Stellar Photometry in Images

- Lab 5: Measuring the Transit of an Exoplanet
  - Determines the radius of the planet (and it's orbital period if observe multiple transits).
- The basic method is to measure the brightnesses of stars in images.
  - Will perform differential photometry by using stars in the field with known magnitudes.

Photometry in Images

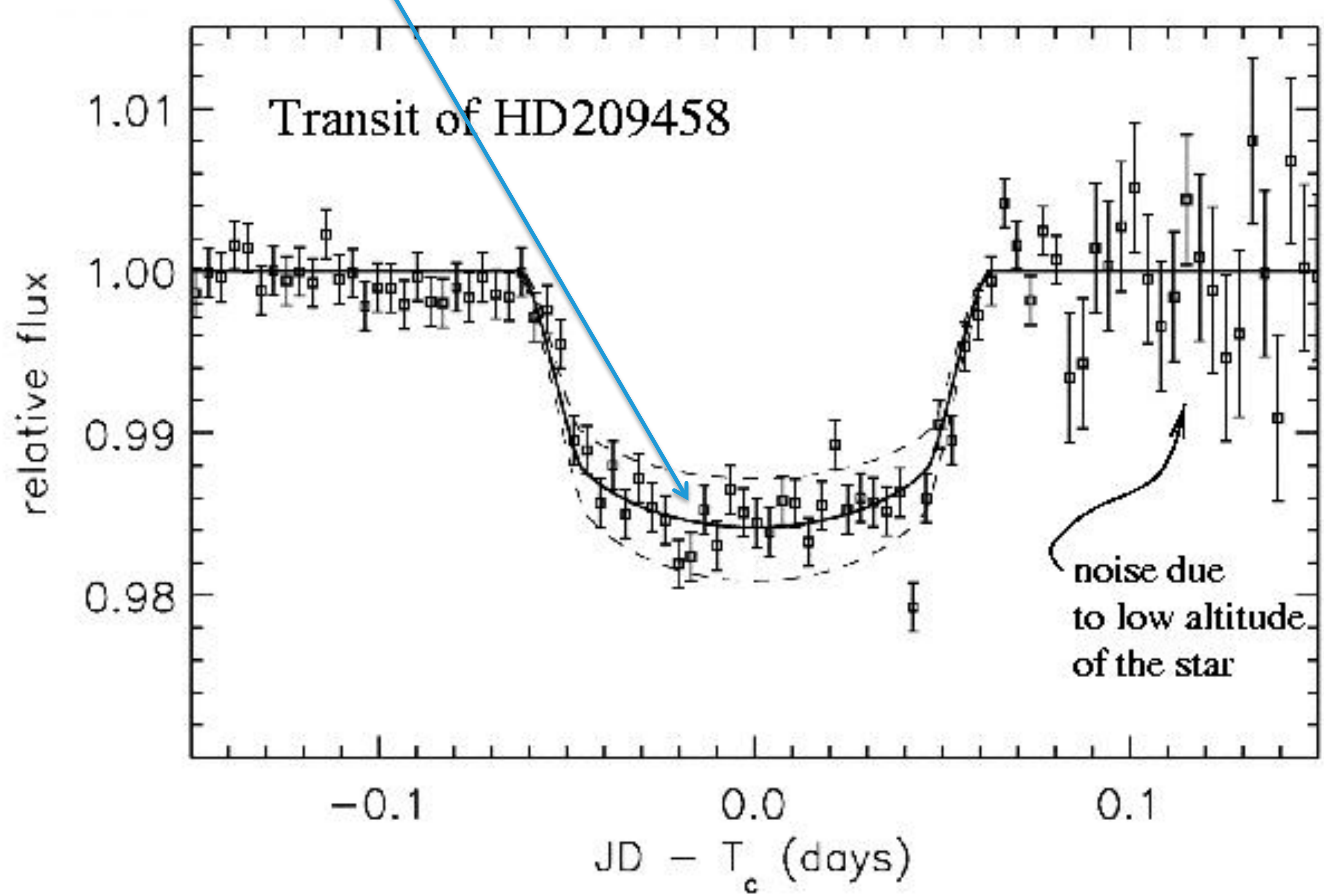
- Correct the image to a uniform, linear response.
  - Dark current and bias level subtraction either
    - done at the telescope with *autodark* subtraction or
    - done by taking separate dark images and subtracting them from the science images later.
  - Need to create an average image of a uniformly illuminated field ("flat field") and divide by it.
    - The mkflatru command.
- Identify your target and comparison stars.
- Measure the brightness of stars in all of the images.

Exoplanet Transits and Eclipses

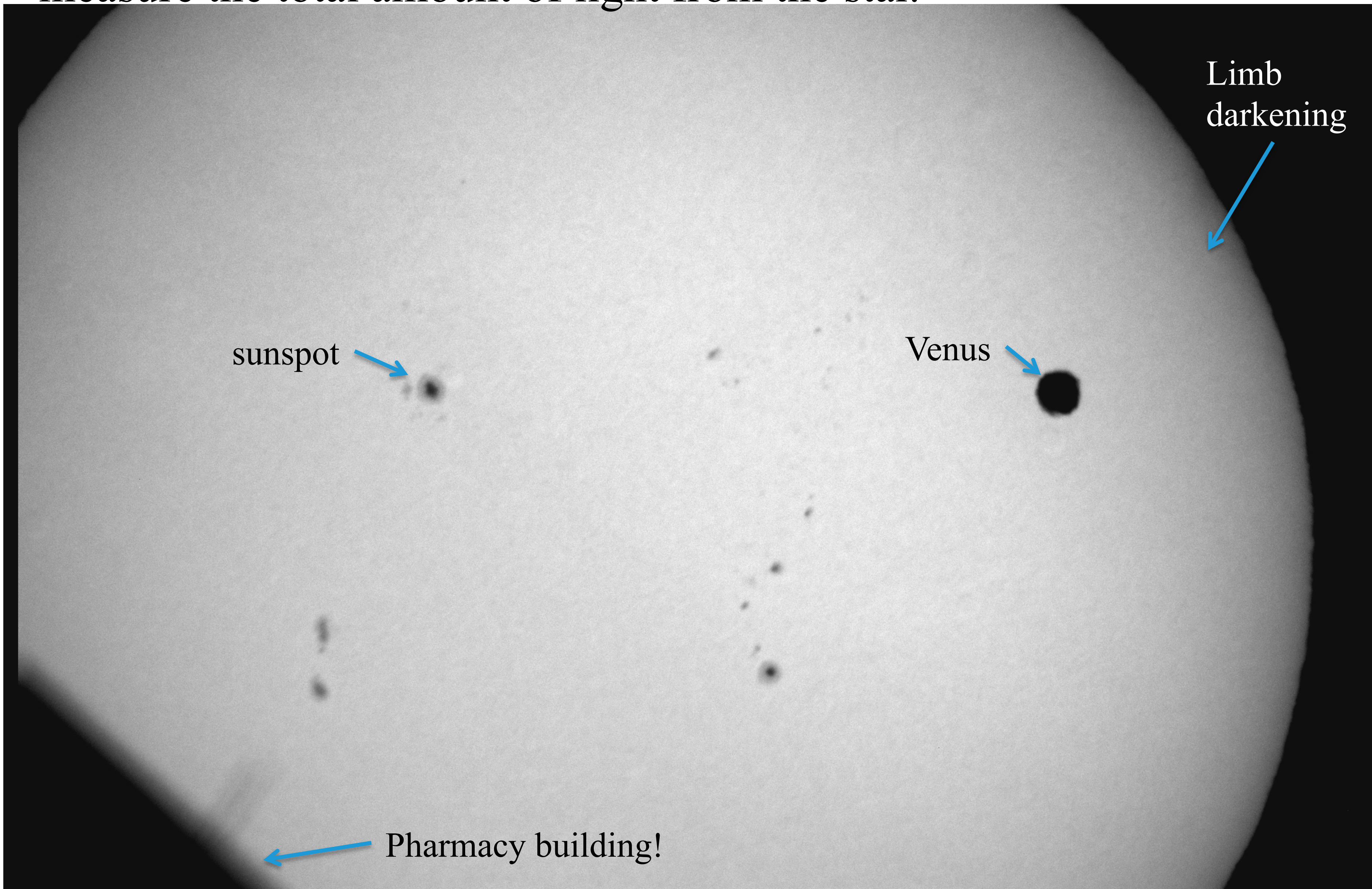


- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and this tells us the planet's radius (if the star's radius is known).
- Because the orbit must be nearly edge on, such systems can yield accurate measurements of planetary mass.

An example of a light curve for the first known transiting exoplanet. Note the curvature due to the non-constant stellar surface brightness.

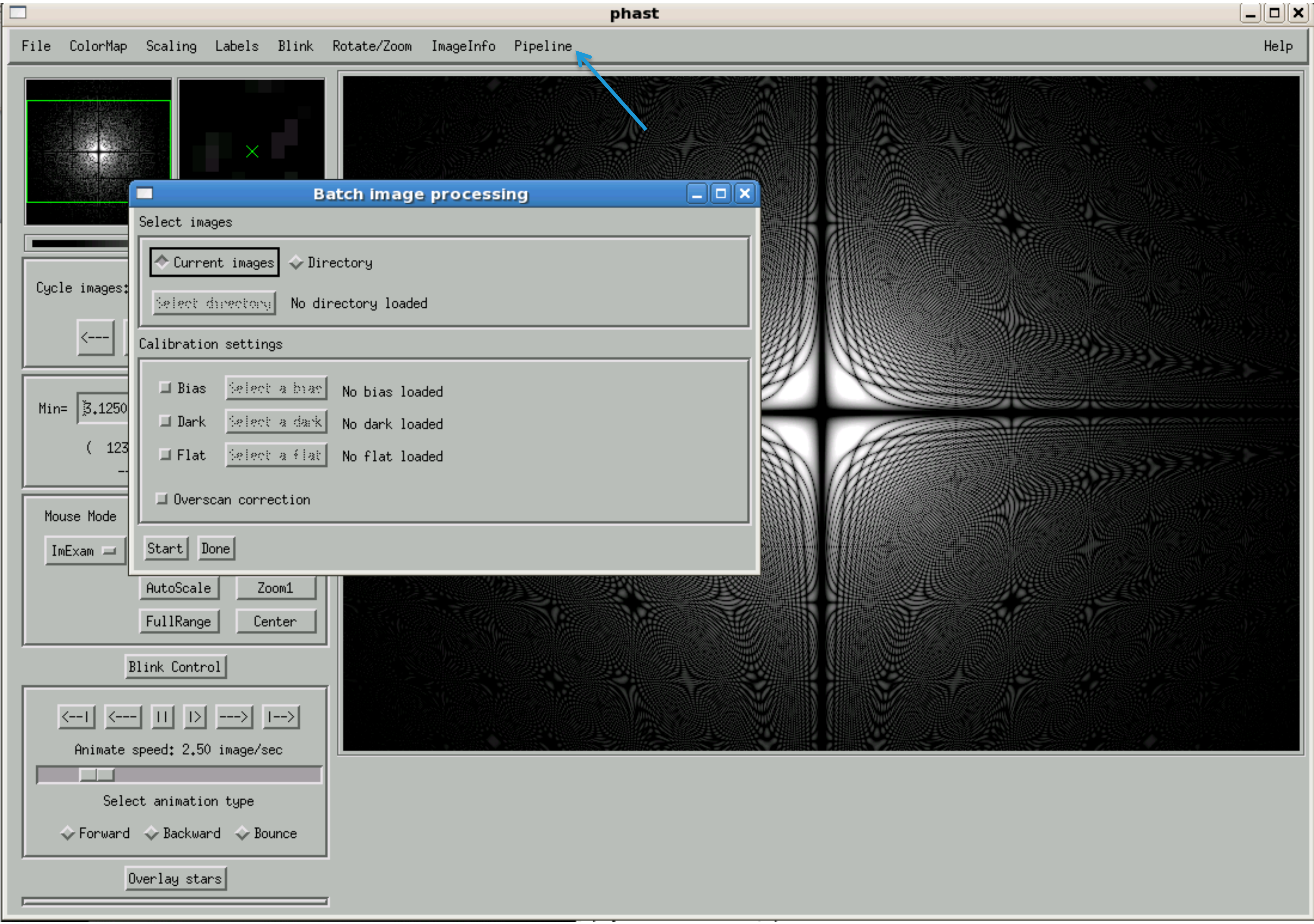


An analogy is the transit of Venus across the Sun observed at the Schommer Observatory this summer. With exoplanets we can only measure the total amount of light from the star.



Data Analysis
Stellar Photometry in Images

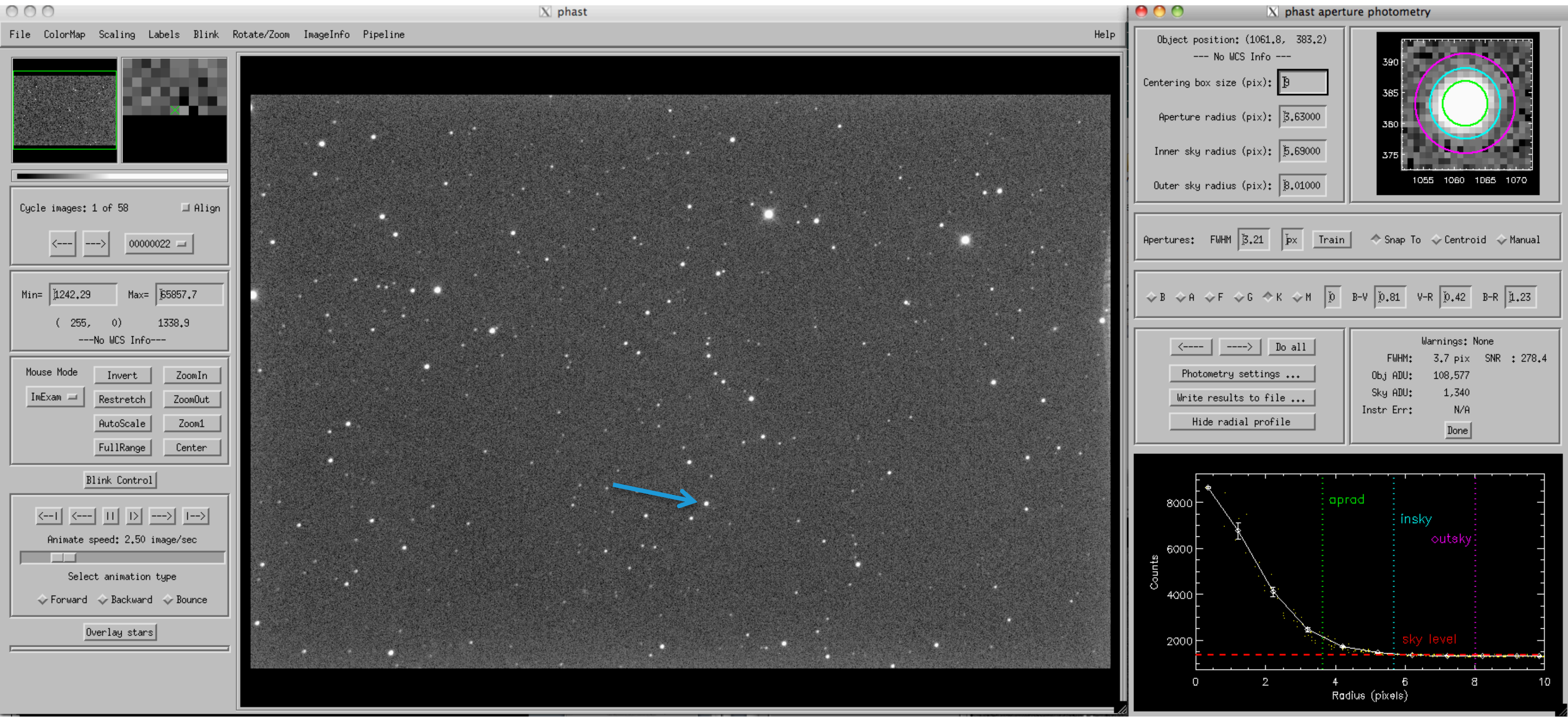
- Correct the image to a uniform, linear response.
  - Autodark subtracted images; divide by flat using batch image processing.
- Identify your target and comparison stars.
  - Comparison stars should be bright, but not saturated.
- Measure the brightness of each star in all of the images.
  - Use the PhAst aperture photometry tool.


phast
File
ColorMap
Scaling
Labels
Blink
Rotate/Zoom
ImageInfo
Pipeline
Help
Batch image processing
Select images
Current images
Directory
Select directory
No directory loaded
Calibration settings
Bias
Select a bias
No bias loaded
Dark
Select a dark
No dark loaded
Flat
Select a flat
No flat loaded
Overscan correction
Start
Done
Cycle images:
<---
Min=
3.1250
Mouse Mode
ImExam
AutoScale
Zoom1
FullRange
Center
Blink Control
<--|
<---
||
|>
--->
|-->
Animate speed: 2.50 image/sec
Select animation type
Forward
Backward
Bounce
Overlay stars

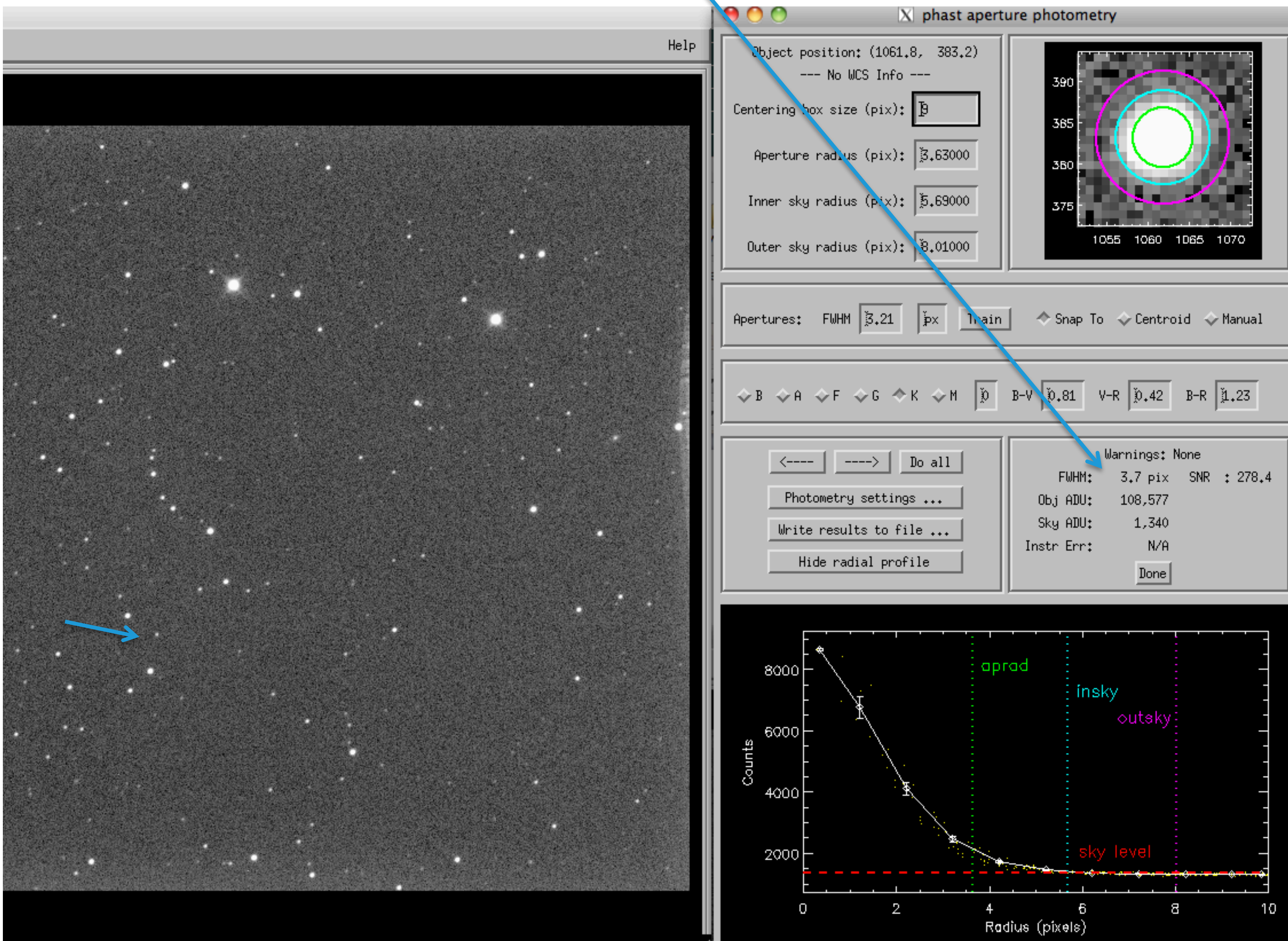
Data Analysis
Stellar Photometry in Images

- Correct the image to a uniform, linear response.
  - Autodark subtracted images; divide by flat using batch image processing.
- Identify your target and comparison stars.
  - Comparison stars should be bright, but not saturated.
- Measure the brightness of each star in all of the images.
  - Use the PhAst aperture photometry tool.

In ImExam mouse mode, left-click on your target star (TrES-3 b here) to bring up the aperture photometry window.



Note the FWHM of the stellar images. Decide on the aperture size.



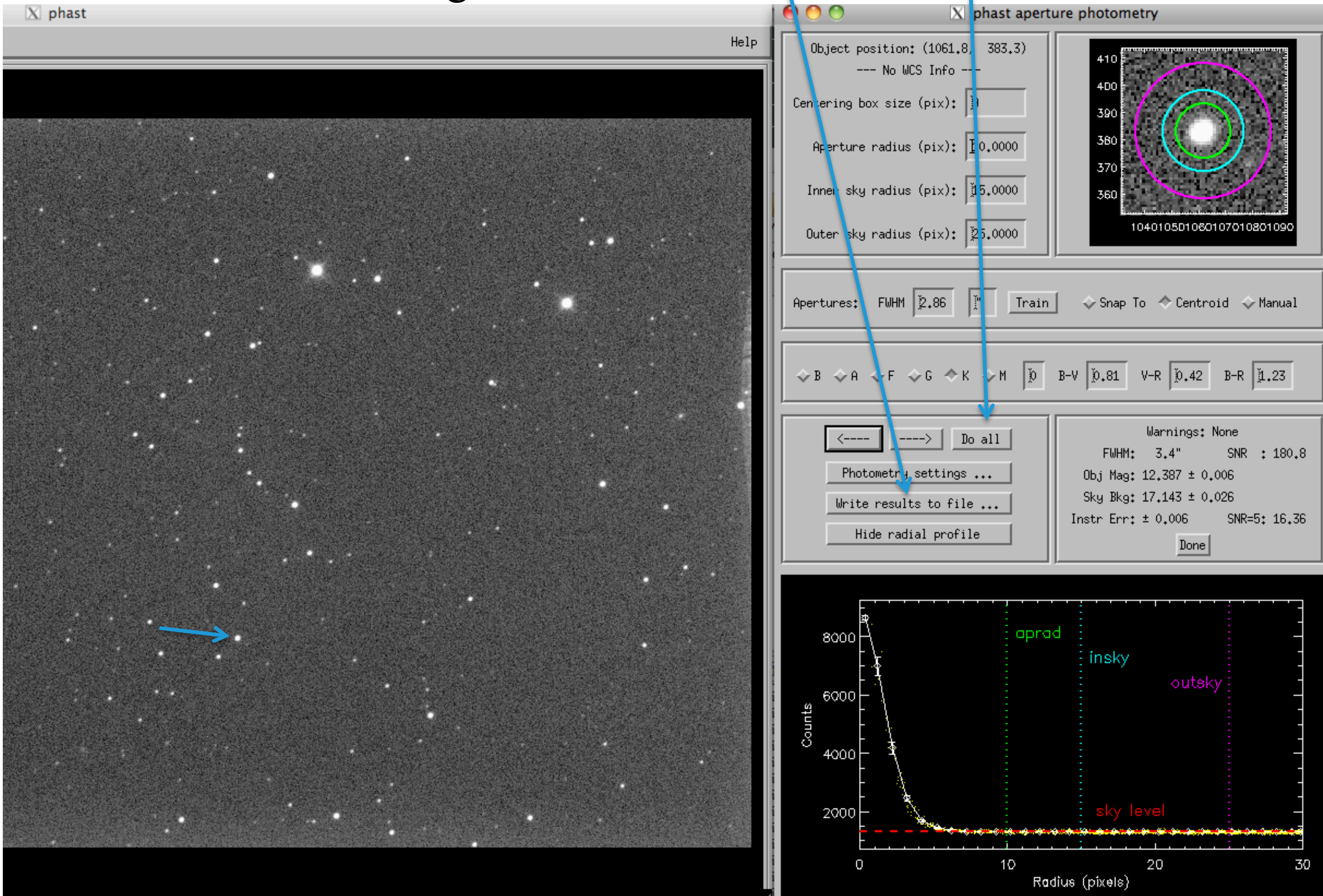
Measuring Stellar Brightness

- Choosing an Aperture Size
  - Compromise on an intermediate size that contains a fixed fraction of the light.
    - This lab compares the brightness of stars in the same image (*differential photometry*), so a fixed fractional loss is OK as long as it is constant across the image.
  - Thus, the size needs to be bigger than the time- and spatially-variable core of the PSF.
  - Rule of thumb: aperture radius = 2 × FWHM of the stellar profile. In this lab, the stars are bright enough that noise from the sky is less important and can err on the side of even larger apertures.
    - Compensates for less-than-perfect guiding and variable PSF.

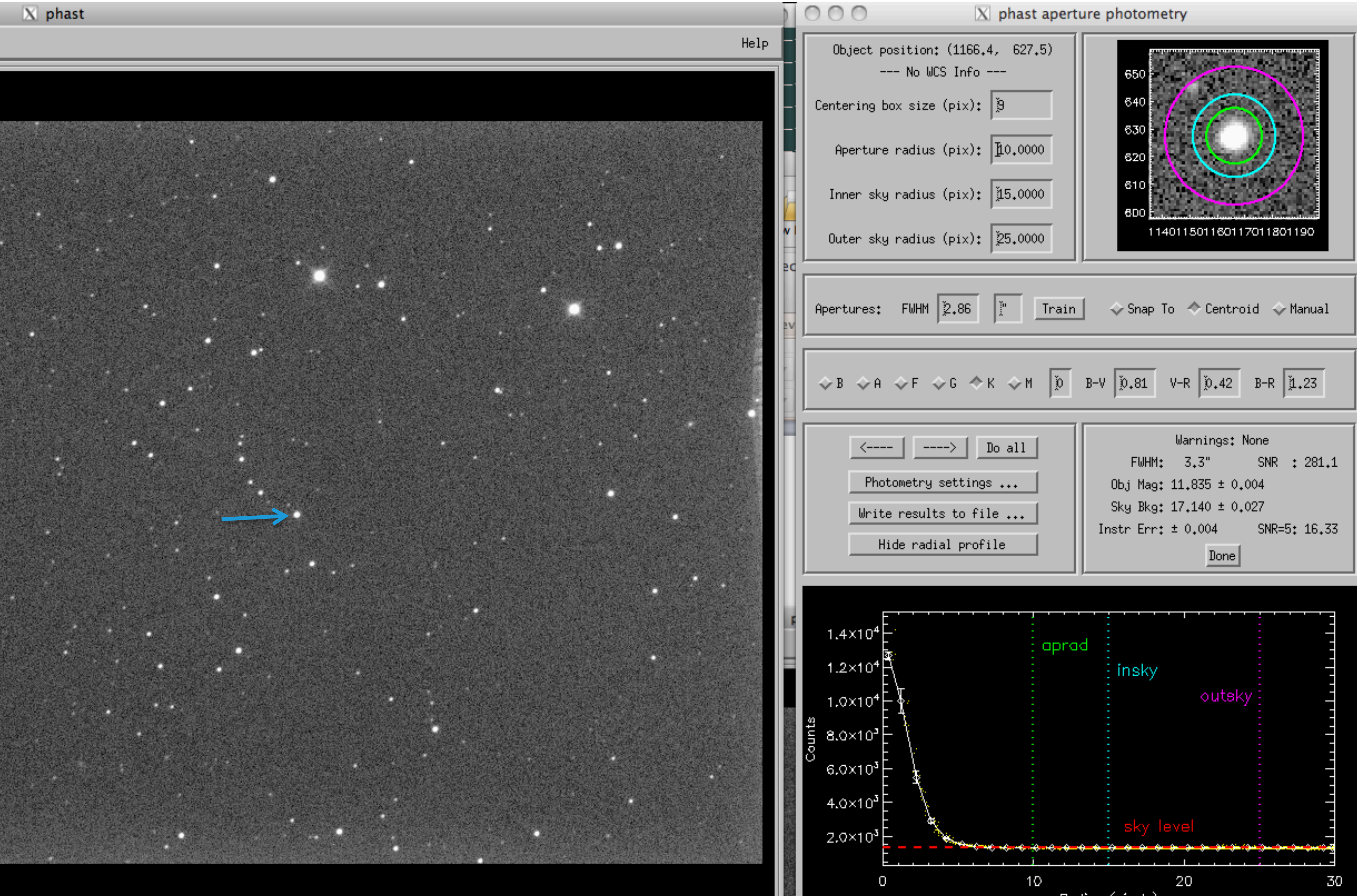
Measuring Stellar Brightness

- RUPhAst aperture photometry measures (x,y) position, “object counts” (*c*), “sky level” (*s* in counts/pixel), and exposure time (*t* in seconds, from the image header).
  - Can only measure *non-saturated* stars.
- Calculates instrumental magnitudes using
  - $m_{inst} = 20.3 - 2.5 \log_{10}(c/t)$
  - $\sigma_m = 1.086\ (\sigma_c/c) = 1.086((c\ g + N_p s\ g + N_p\ r^2)^{1/2}/(g\ c))$
    - g = gain = 0.80 electrons/ADU
    - r = read noise = 15.5 electrons/pixel

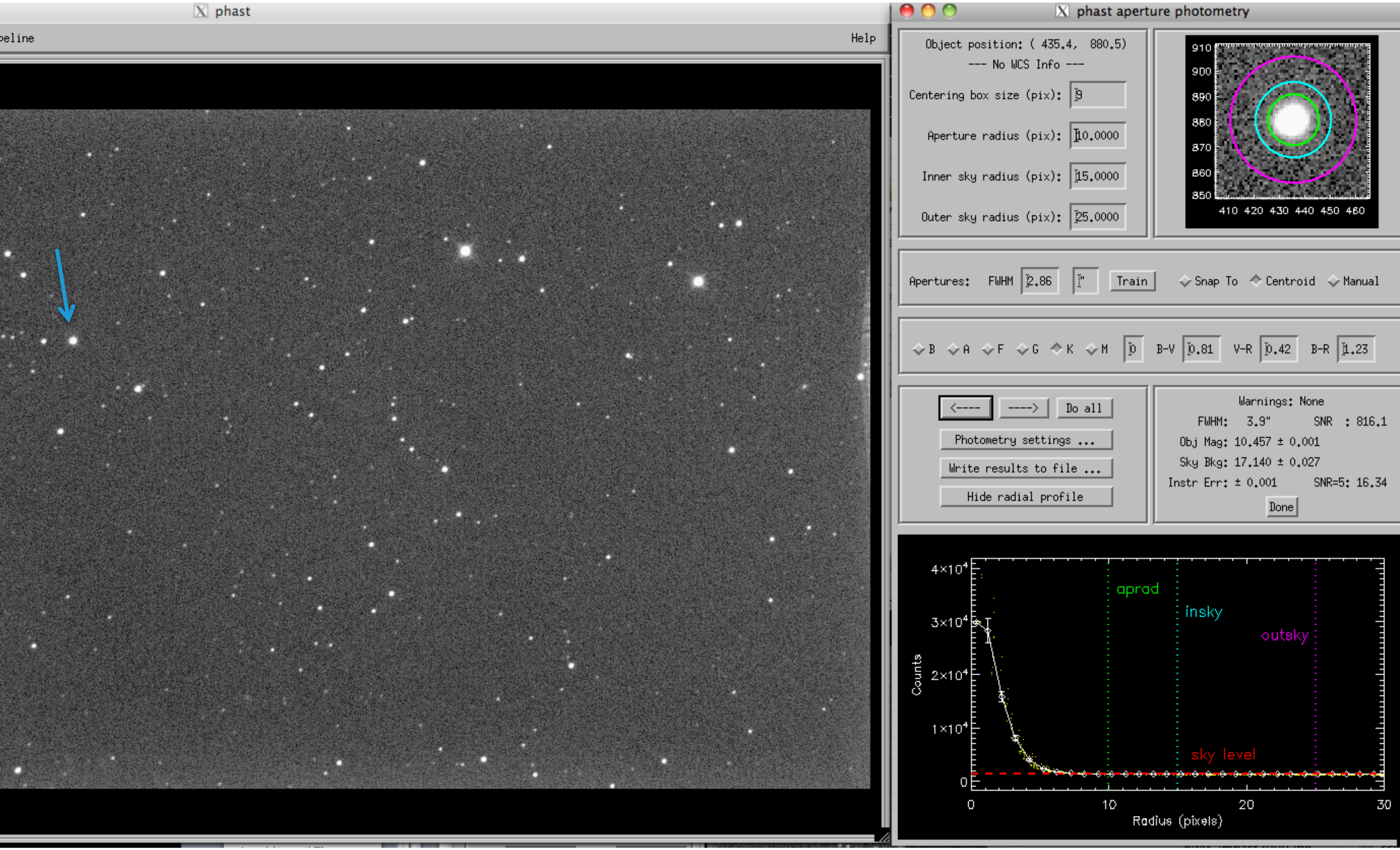
Can open a file to save the photometry in and then photometer the star in all of the loaded images with the "Do all" button.



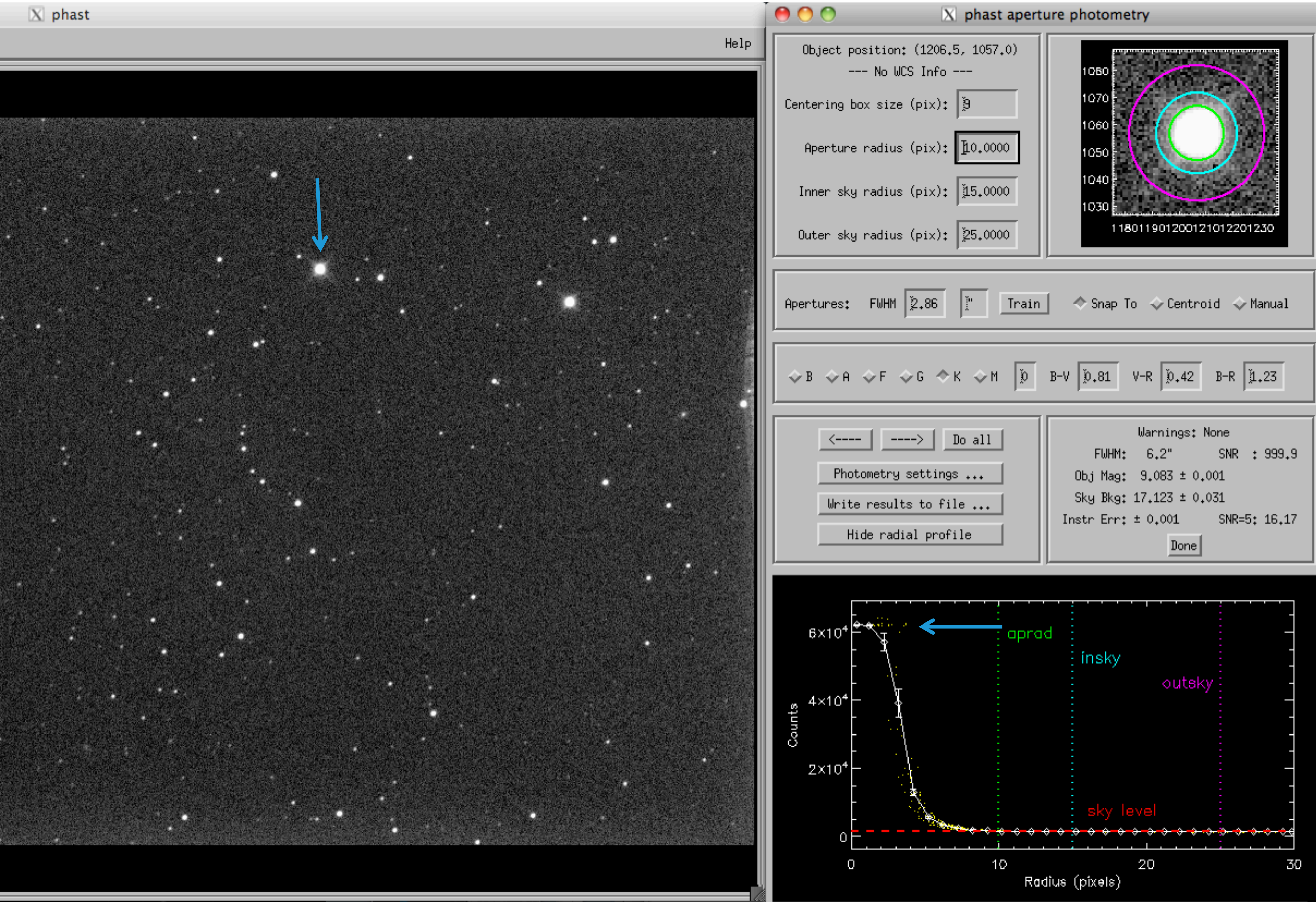
Choose comparison stars with a brightness similar to or greater than the target star. This minimizes the uncertainty in the magnitude difference.



An even brighter comparison star.



But don’t use saturated stars.



Photometry Output from RUPhAst

img	UT	x	y	r	insky	outsky	sky	mag	err	fwhm
0	1.2744 V	1277.9	533.9	12.0	18.0	28.0	16.6998	11.8501	0.0044	4.16
1	1.3615 V	1278.0	533.8	12.0	18.0	28.0	16.7346	11.8373	0.0043	4.33
2	1.4024 V	1277.9	533.7	12.0	18.0	28.0	16.7505	11.8346	0.0042	4.64
3	1.4432 V	1277.9	534.0	12.0	18.0	28.0	16.7631	11.8320	0.0042	4.50
4	1.4840 V	1278.0	533.9	12.0	18.0	28.0	16.7955	11.8278	0.0041	4.64
5	1.5249 V	1277.9	534.3	12.0	18.0	28.0	16.8136	11.8209	0.0041	4.36
6	1.5660 V	1277.8	534.3	12.0	18.0	28.0	16.8276	11.8265	0.0042	4.60
7	1.6069 V	1277.8	533.8	12.0	18.0	28.0	16.8442	11.8181	0.0040	4.40
8	1.6477 V	1277.9	534.2	12.0	18.0	28.0	16.8588	11.8104	0.0041	4.84
9	1.6886 V	1277.8	533.7	12.0	18.0	28.0	16.8742	11.8158	0.0041	4.40
10	1.7295 V	1277.8	534.2	12.0	18.0	28.0	16.8881	11.8028	0.0040	4.53
11	1.7762 V	1277.7	533.9	12.0	18.0	28.0	16.9132	11.8159	0.0040	4.47
12	1.8171 V	1277.7	533.6	12.0	18.0	28.0	16.9279	11.8045	0.0039	4.67
13	1.8580 V	1277.6	533.9	12.0	18.0	28.0	16.9442	11.8090	0.0038	4.84
14	1.8990 V	1277.7	533.9	12.0	18.0	28.0	16.9618	11.8039	0.0038	4.50
15	1.9399 V	1277.7	533.8	12.0	18.0	28.0	16.9759	11.7972	0.0039	4.06
16	1.9808 V	1277.7	533.8	12.0	18.0	28.0	16.9886	11.8036	0.0038	4.81
17	2.0216 V	1277.7	533.9	12.0	18.0	28.0	17.0052	11.7985	0.0037	4.40
18	2.0624 V	1277.7	534.0	12.0	18.0	28.0	17.0170	11.7915	0.0037	4.81
19	2.1032 V	1277.7	534.0	12.0	18.0	28.0	17.0335	11.7960	0.0037	4.64
20	2.1441 V	1277.6	534.0	12.0	18.0	28.0	17.0484	11.7964	0.0037	4.84
21	2.1857 V	1277.3	534.4	12.0	18.0	28.0	17.0564	11.7825	0.0038	5.08
22	2.2269 V	1277.6	534.1	12.0	18.0	28.0	17.0813	11.7706	0.0037	5.25
23	2.2677 V	1277.7	533.9	12.0	18.0	28.0	17.0871	11.7685	0.0037	4.70
24	2.3087 V	1277.4	534.0	12.0	18.0	28.0	17.0984	11.7674	0.0035	5.01
25	2.3498 V	1277.5	533.8	12.0	18.0	28.0	17.1218	11.7764	0.0037	5.08
26	2.3906 V	1277.5	534.3	12.0	18.0	28.0	17.1723	11.7639	0.0035	5.49
27	2.4316 V	1277.4	533.9	12.0	18.0	28.0	17.1906	11.7671	0.0035	5.66
28	2.4726 V	1277.3	533.9	12.0	18.0	28.0	17.2092	11.7700	0.0034	5.52
29	2.5134 V	1277.3	534.1	12.0	18.0	28.0	17.2230	11.7555	0.0034	NaN
30	2.5546 V	1277.5	533.8	12.0	18.0	28.0	17.2409	11.7514	0.0035	5.45
31	2.5988 V	1277.1	534.2	12.0	18.0	28.0	17.2492	11.7580	0.0034	6.24

Photometry Output in Excel

STDEV.P | fx =J4-J77

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	img	UT		x	y	r	insky	outsky	sky	mag	err	fwhm	
3													
4	0	1.2744	V	1277.9	533.9	12	18	28	16.6998	11.8501	0.0044	4.16	
5	1	1.3615	V	1278	533.8	12	18	28	16.7346	11.8373	0.0043	4.33	
6	2	1.4024	V	1277.9	533.7	12	18	28	16.7505	11.8346	0.0042	4.64	
7	3	1.4432	V	1277.9	534	12	18	28	16.7631	11.832	0.0042	4.5	
8	4	1.484	V	1278	533.9	12	18	28	16.7955	11.8278	0.0041	4.64	
9	5	1.5249	V	1277.9	534.3	12	18	28	16.8136	11.8209	0.0041	4.36	
10	6	1.566	V	1277.8	534.3	12	18	28	16.8276	11.8265	0.0042	4.6	
11	7	1.6069	V	1277.8	533.8	12	18	28	16.8442	11.8181	0.004	4.4	
12	8	1.6477	V	1277.9	534.2	12	18	28	16.8588	11.8104	0.0041	4.84	
13	9	1.6886	V	1277.8	533.7	12	18	28	16.8742	11.8158	0.0041	4.4	
14	10	1.7295	V	1277.8	534.2	12	18	28	16.8881	11.8028	0.004	4.53	
15	11	1.7762	V	1277.7	533.9	12	18	28	16.9132	11.8159	0.004	4.47	
16	12	1.8171	V	1277.7	533.6	12	18	28	16.9279	11.8045	0.0039	4.67	
17	13	1.858	V	1277.6	533.9	12	18	28	16.9442	11.809	0.0038	4.84	
18	14	1.899	V	1277.7	533.9	12	18	28	16.9618	11.8039	0.0038	4.5	
19	15	1.9399	V	1277.7	533.8	12	18	28	16.9759	11.7972	0.0039	4.06	
20	16	1.9808	V	1277.7	533.8	12	18	28	16.9886	11.8036	0.0038	4.81	
21	17	2.0216	V	1277.7	533.9	12	18	28	17.0052	11.7985	0.0037	4.4	
22	18	2.0624	V	1277.7	534	12	18	28	17.017	11.7915	0.0037	4.81	
23	19	2.1032	V	1277.7	534	12	18	28	17.0335	11.796	0.0037	4.64	
24	20	2.1441	V	1277.6	534	12	18	28	17.0484	11.7964	0.0037	4.84	
25	21	2.1857	V	1277.3	534.4	12	18	28	17.0564	11.7825	0.0038	5.08	
26	22	2.2269	V	1277.6	534.1	12	18	28	17.0813	11.7706	0.0037	5.25	
27	23	2.2677	V	1277.7	533.9	12	18	28	17.0871	11.7685	0.0037	4.7	
76													
77	0	1.2744	V	1527.8	1214.2	12	18	28	16.7003	11.9411	0.0048	4.67	
78	1	1.3615	V	1527.9	1214.3	12	18	28	16.735	11.9304	0.0049	4.7	
79	2	1.4024	V	1527.7	1214.1	12	18	28	16.7532	11.9134	0.0047	4.98	
80	3	1.4432	V	1527.8	1214.4	12	18	28	16.7622	11.9266	0.0048	4.5	
81	4	1.484	V	1527.9	1214.3	12	18	28	16.7977	11.9075	0.0046	4.74	
82	5	1.5249	V	1527.8	1214.8	12	18	28	16.8132	11.9131	0.0048	4.3	
83	6	1.566	V	1527.6	1214.8	12	18	28	16.8286	11.9126	0.0046	4.5	
84	7	1.6069	V	1527.6	1214.3	12	18	28	16.8449	11.9041	0.0046	4.84	
85	8	1.6477	V	1527.7	1214.7	12	18	28	16.8582	11.8949	0.0046	4.5	
86	9	1.6886	V	1527.6	1214.2	12	18	28	16.8744	11.8965	0.0045	4.81	
87	10	1.7295	V	1527.6	1214.7	12	18	28	16.8879	11.889	0.0045	4.43	
88	11	1.7762	V	1527.6	1214.4	12	18	28	16.9125	11.8894	0.0044	4.74	
89	12	1.8171	V	1527.4	1214	12	18	28	16.9291	11.8804	0.0044	4.87	

"Import" the text file from RUPhAst into Microsoft Excel or the OpenOffice Calc program.

A fixed-width input format works best.

Delete extra lines and rearrange blocks of photometry in Excel/Calc (or earlier with a text editor).

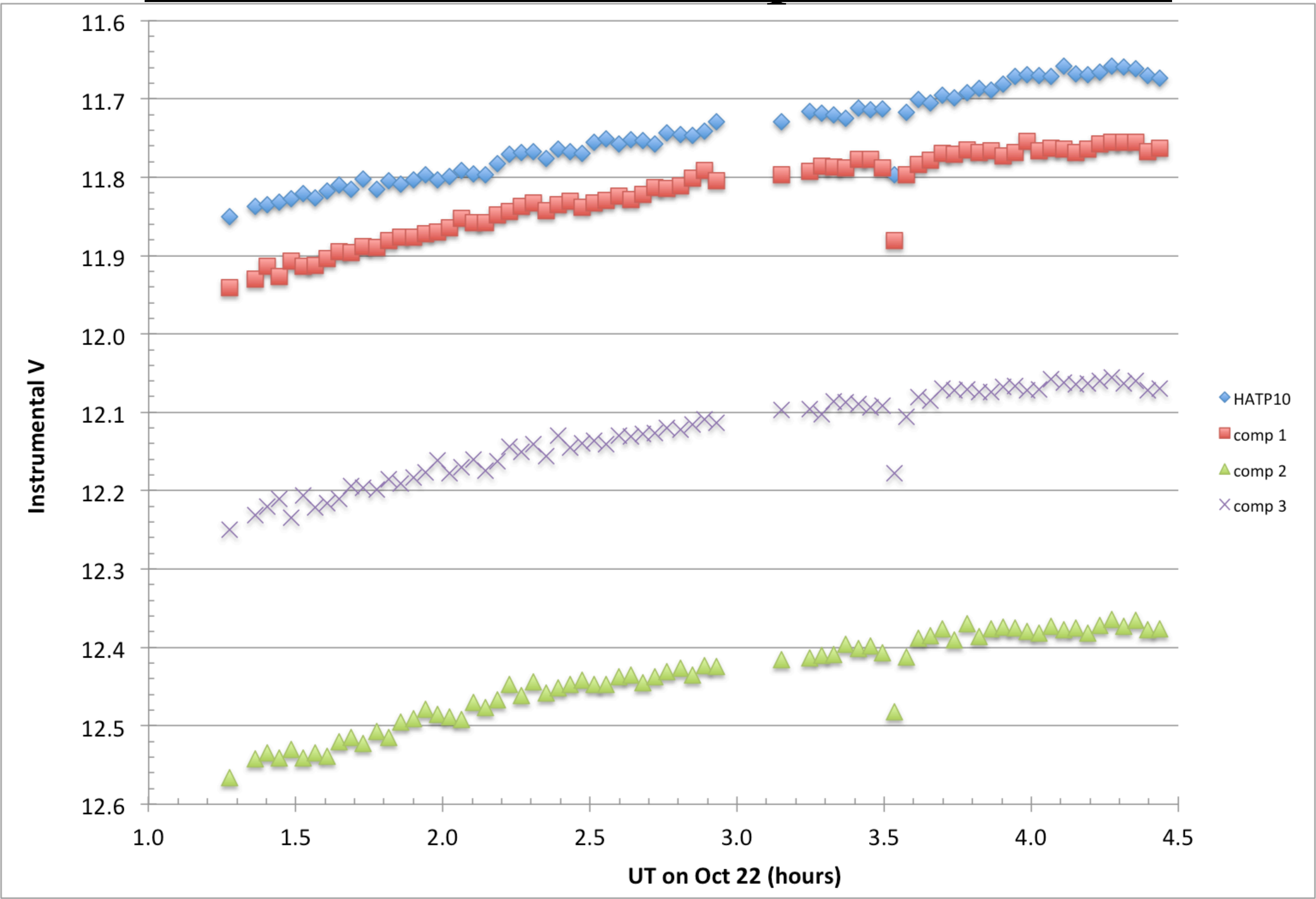
Photometry Output in Excel

Calculate the difference between the magnitudes of the target and comparison stars at each time. Also the uncertainty.

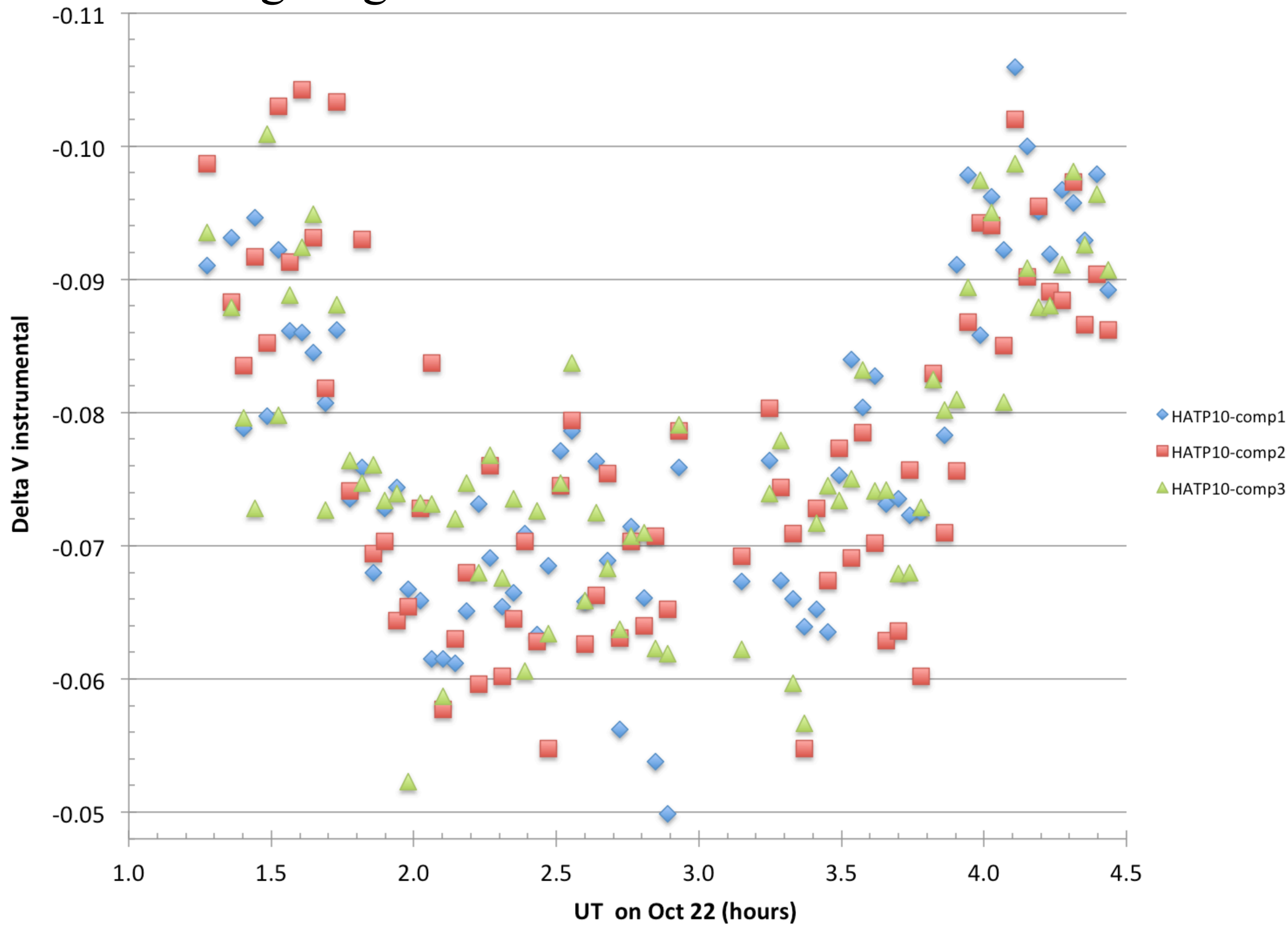
M	N	O	P	Q	R	S	T	U
	hatp10-c1	unc	hatp10-c2	unc	hatp10-c3		hatp10-avg	
	=J4-J77	0.0065	-0.0987	0.0094	-0.0935	0.0077	-0.0944	0.0046
	-0.0931	0.0065	-0.0883	0.0091	-0.0879	0.0074	-0.0898	0.0046
	-0.0788	0.0063	-0.0835	0.0089	-0.0796	0.0072	-0.0806	0.0046
	-0.0946	0.0064	-0.0917	0.0088	-0.0728	0.0074	-0.0864	0.0046
	-0.0797	0.0062	-0.0852	0.0087	-0.1009	0.0073	-0.0886	0.0046
	-0.0922	0.0063	-0.1030	0.0088	-0.0798	0.0071	-0.0917	0.0046
	-0.0861	0.0062	-0.0913	0.0088	-0.0888	0.0072	-0.0887	0.0046
	-0.0860	0.0061	-0.1042	0.0087	-0.0924	0.0070	-0.0942	0.0046
	-0.0845	0.0062	-0.0931	0.0086	-0.0949	0.0069	-0.0908	0.0046
	-0.0807	0.0061	-0.0818	0.0085	-0.0727	0.0069	-0.0784	0.0046
	-0.0862	0.0060	-0.1033	0.0083	-0.0881	0.0070	-0.0925	0.0046
	-0.0735	0.0059	-0.0741	0.0083	-0.0764	0.0069	-0.0747	0.0046
	-0.0759	0.0059	-0.0930	0.0083	-0.0747	0.0065	-0.0812	0.0046
	-0.0680	0.0057	-0.0694	0.0081	-0.0761	0.0065	-0.0712	0.0046
	-0.0728	0.0057	-0.0703	0.0081	-0.0734	0.0065	-0.0722	0.0046
	-0.0744	0.0057	-0.0644	0.0079	-0.0739	0.0065	-0.0709	0.0046
	-0.0667	0.0057	-0.0654	0.0080	-0.0523	0.0064	-0.0615	0.0046
	-0.0659	0.0056	-0.0728	0.0079	-0.0732	0.0065	-0.0706	0.0046
	-0.0615	0.0055	-0.0837	0.0079	-0.0731	0.0065	-0.0728	0.0046
	-0.0615	0.0055	-0.0577	0.0077	-0.0587	0.0063	-0.0593	0.0046
	-0.0612	0.0056	-0.0630	0.0077	-0.0720	0.0064	-0.0654	0.0046
	-0.0651	0.0056	-0.0680	0.0077	-0.0747	0.0064	-0.0693	0.0046
	-0.0731	0.0055	-0.0596	0.0076	-0.0680	0.0062	-0.0669	0.0046
	-0.0691	0.0054	-0.0760	0.0077	-0.0768	0.0062	-0.0740	0.0046

76													c1-c2		c1-c3		c1-c2+0.6168		c1-c3+0.3056
77	0	1.2744	V	1527.8	1214.2	12	18	28	16.7003	11.9411	0.0048	4.67	-0.6245	0.0096	-0.3081	0.0079	-0.0077		-0.0025
78	1	1.3615	V	1527.9	1214.3	12	18	28	16.735	11.9304	0.0049	4.7	-0.6120	0.0094	-0.3004	0.0077	0.0048		0.0052
79	2	1.4024	V	1527.7	1214.1	12	18	28	16.7532	11.9134	0.0047	4.98	-0.6215	0.0091	-0.3064	0.0075	-0.0047		-0.0008
80	3	1.4432	V	1527.8	1214.4	12	18	28	16.7622	11.9266	0.0048	4.5	-0.6139	0.0091	-0.2838	0.0078	0.0029		0.0218
81	4	1.484	V	1527.9	1214.3	12	18	28	16.7977	11.9075	0.0046	4.74	-0.6223	0.0090	-0.3268	0.0076	-0.0055		-0.0212
82	5	1.5249	V	1527.8	1214.8	12	18	28	16.8132	11.9131	0.0048	4.3	-0.6276	0.0092	-0.2932	0.0075	-0.0108		0.0124
83	6	1.566	V	1527.6	1214.8	12	18	28	16.8286	11.9126	0.0046	4.5	-0.6220	0.0090	-0.3083	0.0074	-0.0052		-0.0027
84	7	1.6069	V	1527.6	1214.3	12	18	28	16.8449	11.9041	0.0046	4.84	-0.6350	0.0090	-0.3120	0.0074	-0.0182		-0.0064
85	8	1.6477	V	1527.7	1214.7	12	18	28	16.8582	11.8949	0.0046	4.5	-0.6254	0.0089	-0.3160	0.0072	-0.0086		-0.0104
86	9	1.6886	V	1527.6	1214.2	12	18	28	16.8744	11.8965	0.0045	4.81	-0.6179	0.0087	-0.2976	0.0072	-0.0011		0.0080
87	10	1.7295	V	1527.6	1214.7	12	18	28	16.8879	11.889	0.0045	4.43	-0.6339	0.0086	-0.3075	0.0073	-0.0171		-0.0019
88	11	1.7762	V	1527.6	1214.4	12	18	28	16.9125	11.8894	0.0044	4.74	-0.6174	0.0085	-0.3085	0.0071	-0.0006		-0.0029
89	12	1.8171	V	1527.4	1214	12	18	28	16.9291	11.8804	0.0044	4.87	-0.6339	0.0085	-0.3044	0.0068	-0.0171		0.0012

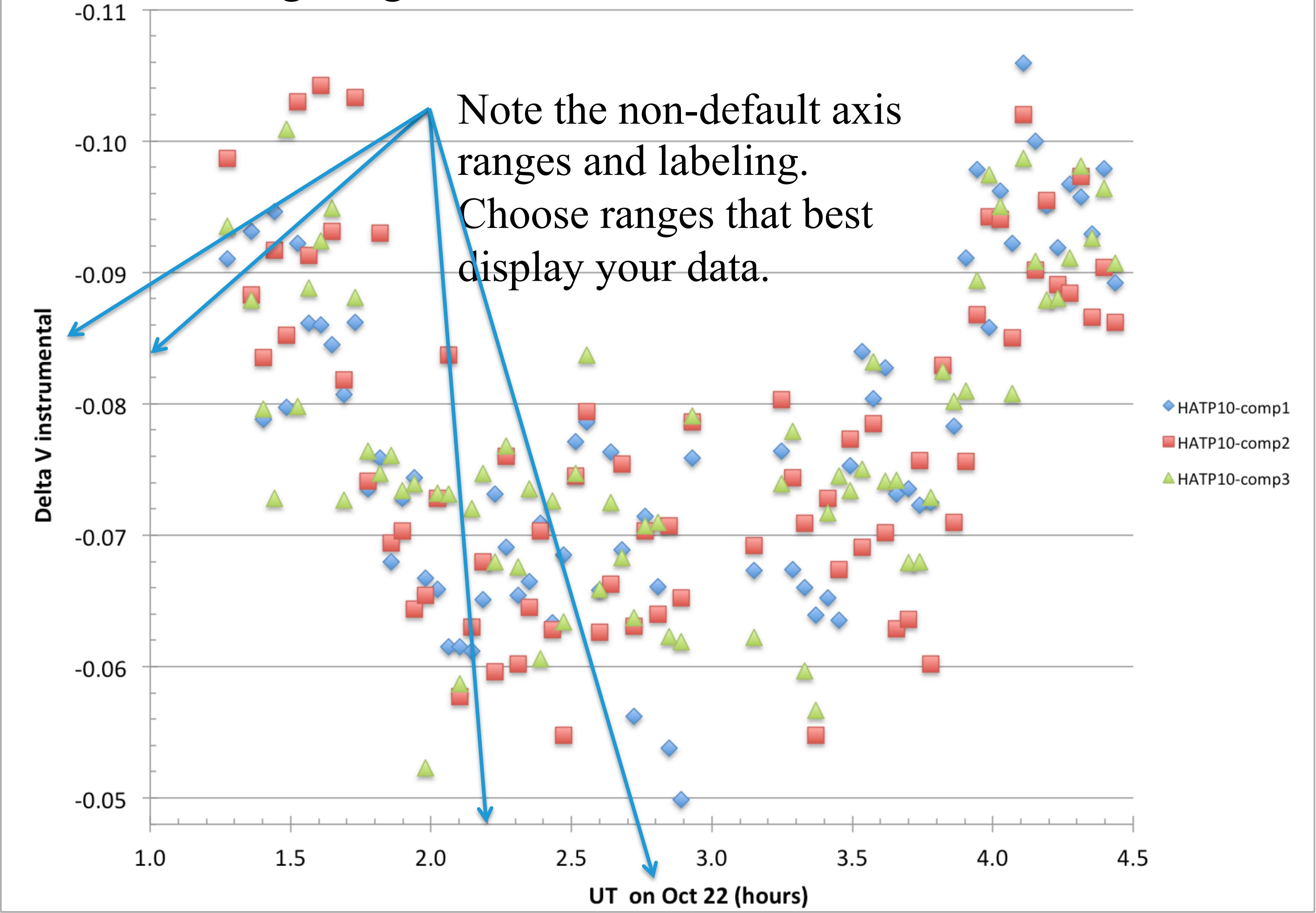
HAT-P-10 and comparison stars



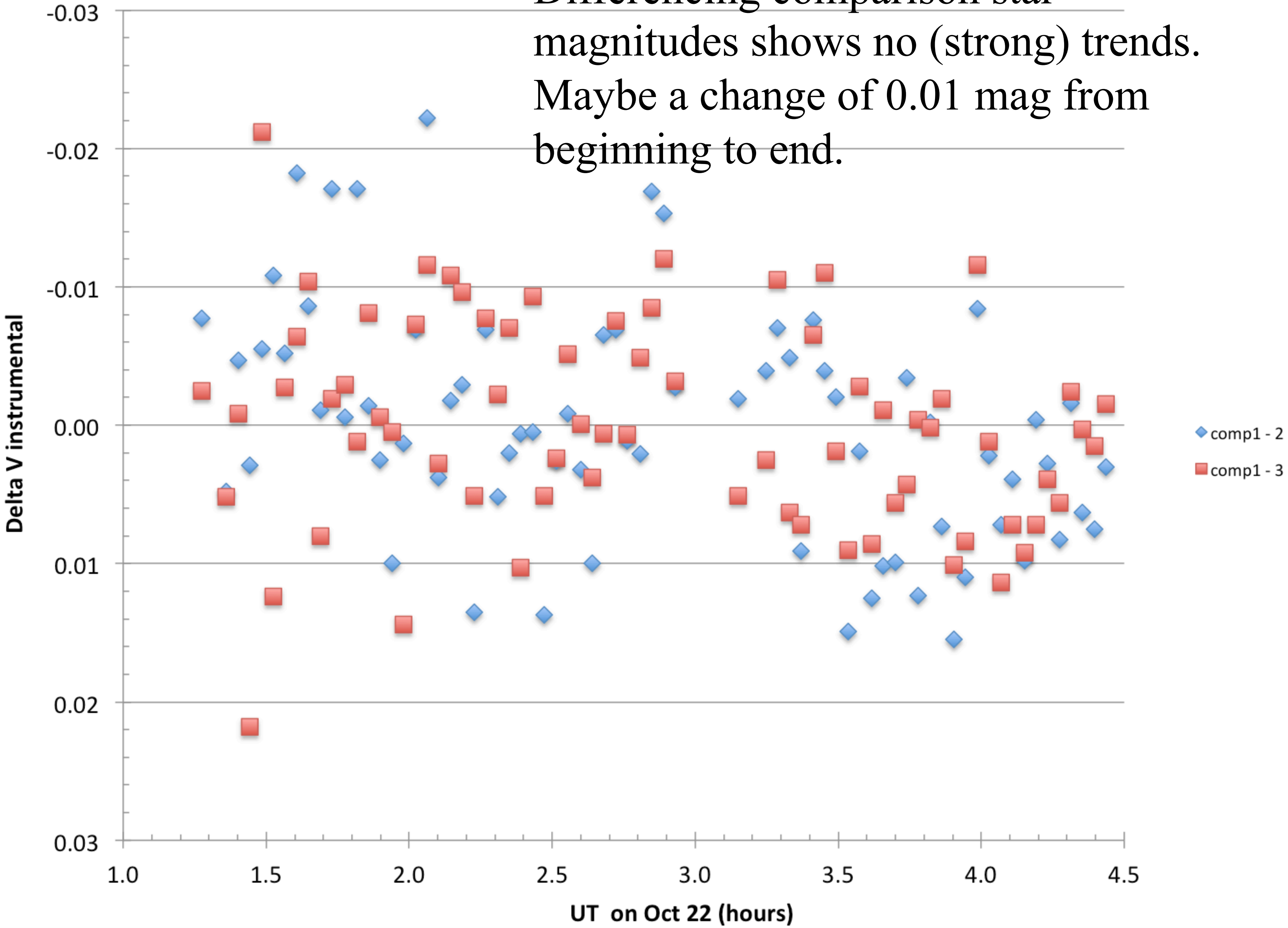
Taking magnitude differences reveals the transit.



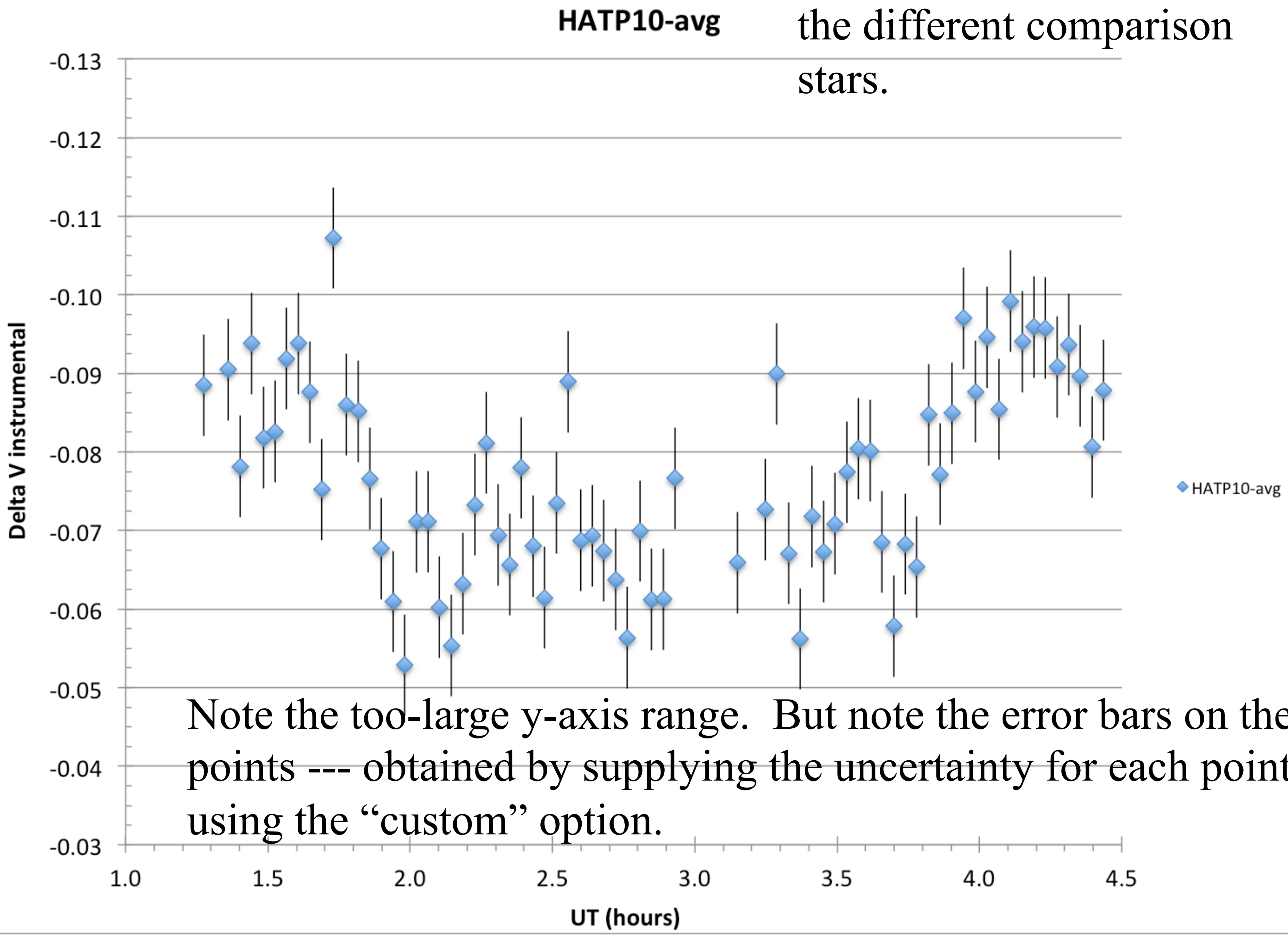
Taking magnitude differences reveals the transit.



Differencing comparison star magnitudes shows no (strong) trends. Maybe a change of 0.01 mag from beginning to end.



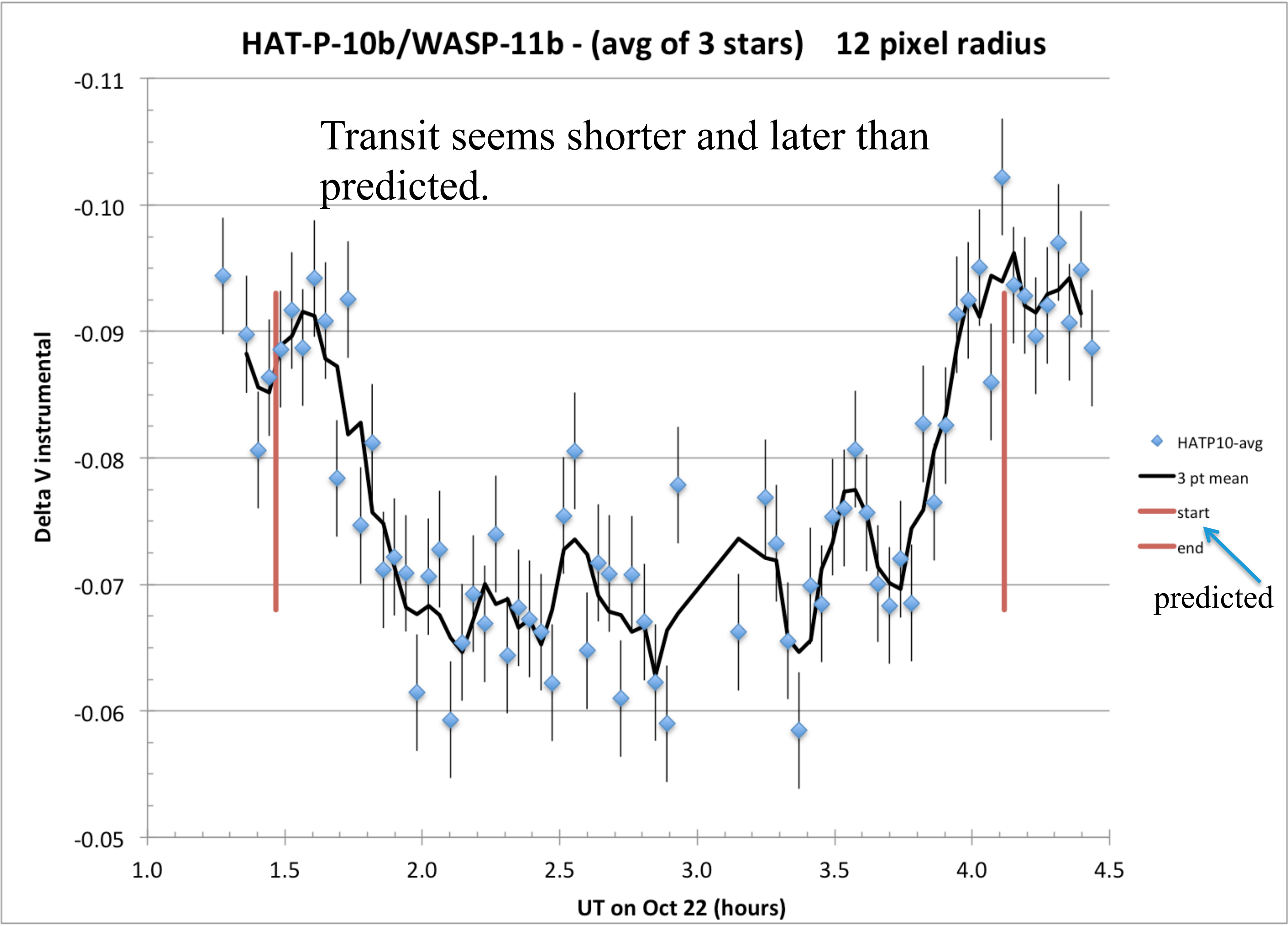
Averaging the results from the different comparison stars.



Note the too-large y-axis range. But note the error bars on the points --- obtained by supplying the uncertainty for each point using the “custom” option.

Lab 5 Analysis

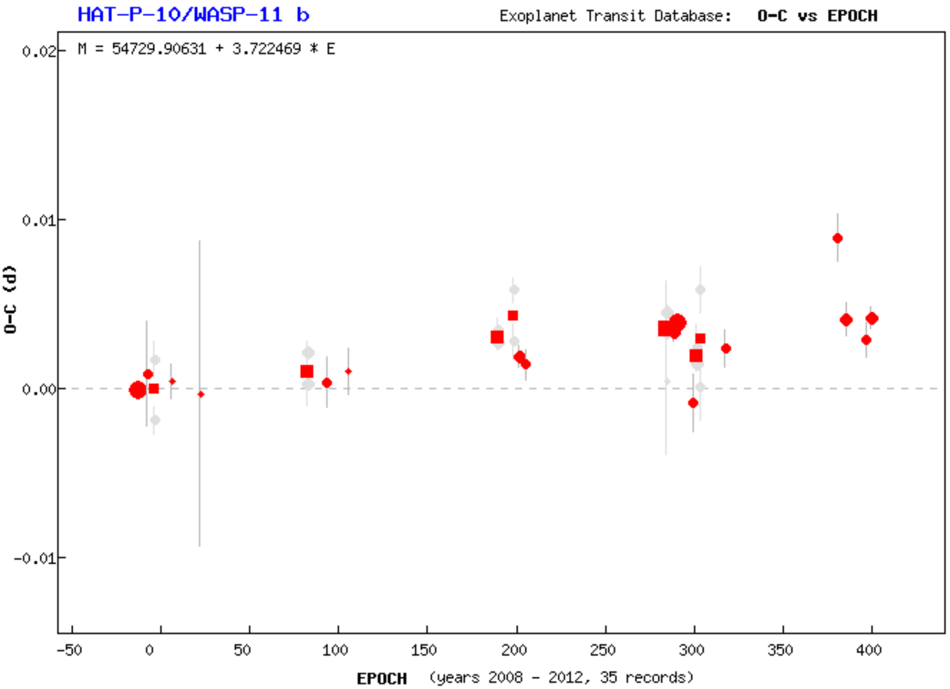
- Once you have your transit light curve, how to quantitatively estimate the depth, duration, and central time?
  - One useful approach it to plot running mean of the data (say three points). The smoother curve can make it easier to see the features of the transit.

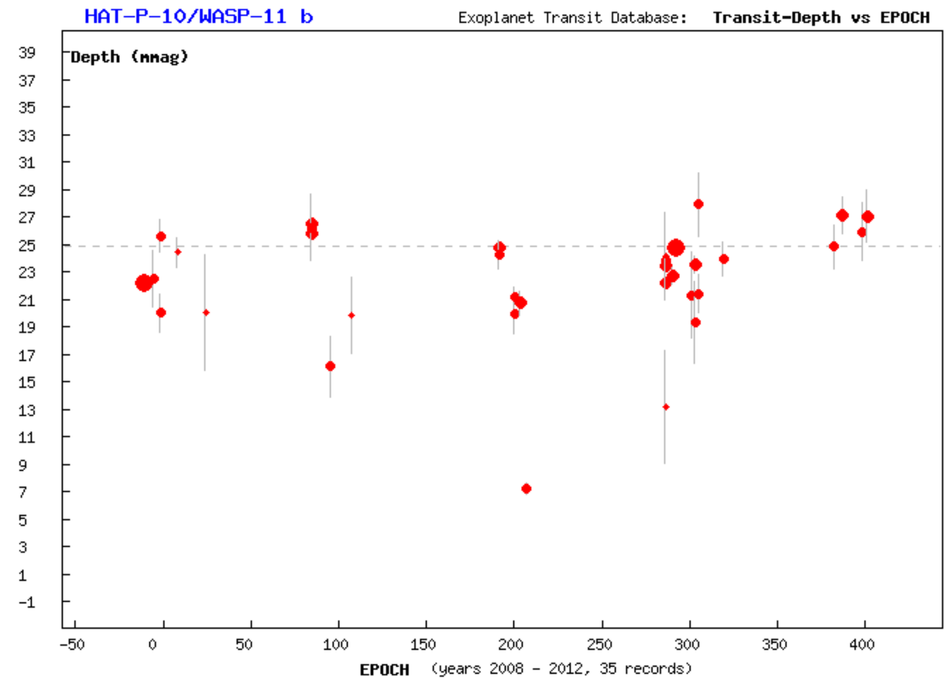

HAT-P-10b/WASP-11b - (avg of 3 stars) 12 pixel radius
Transit seems shorter and later than predicted.
Delta V instrumental
-0.11
-0.10
-0.09
-0.08
-0.07
-0.06
-0.05
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
UT on Oct 22 (hours)
HATP10-avg
3 pt mean
start
end
predicted

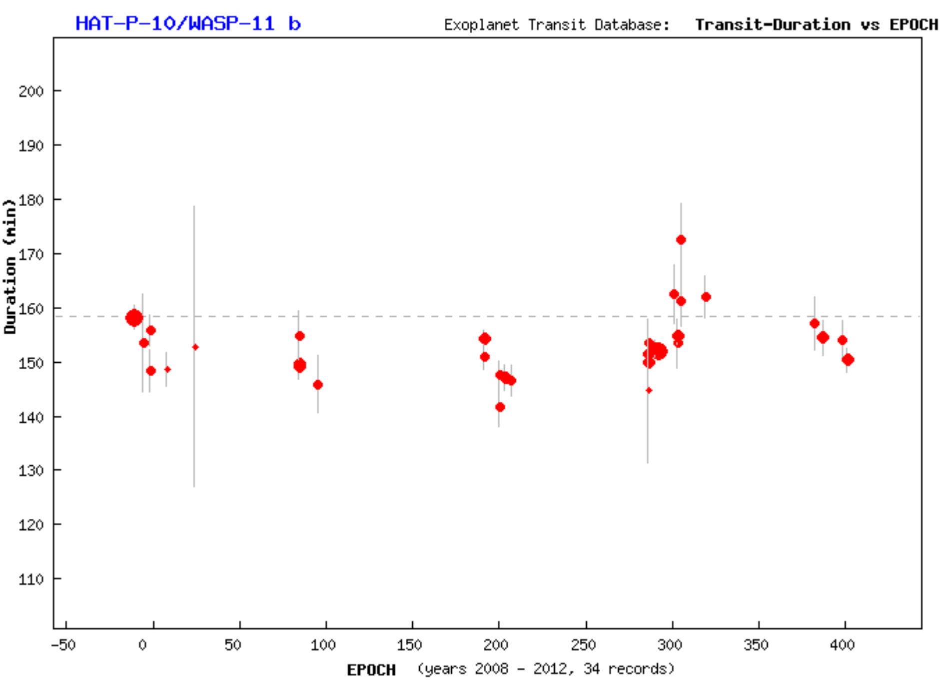
Lab 5 Analysis

- Once you have your transit light curve, how to quantitatively estimate the depth, duration, and central time?
  - One useful approach it to plot a running mean of the data (say three points). The smoother curve can make it easier to see the features of the transit.
  - Averaging the points in and out of transit and taking the difference yields an estimate of the depth.

3pt mean				
-0.0883	out avg =	-0.0912	0.0011	(points 4-11 and 65-74)
-0.0856	in avg=	-0.0689	0.0010	(points 19-53)
-0.0852	diff =	0.0223	0.0015117	
-0.0889				
[illegible]				



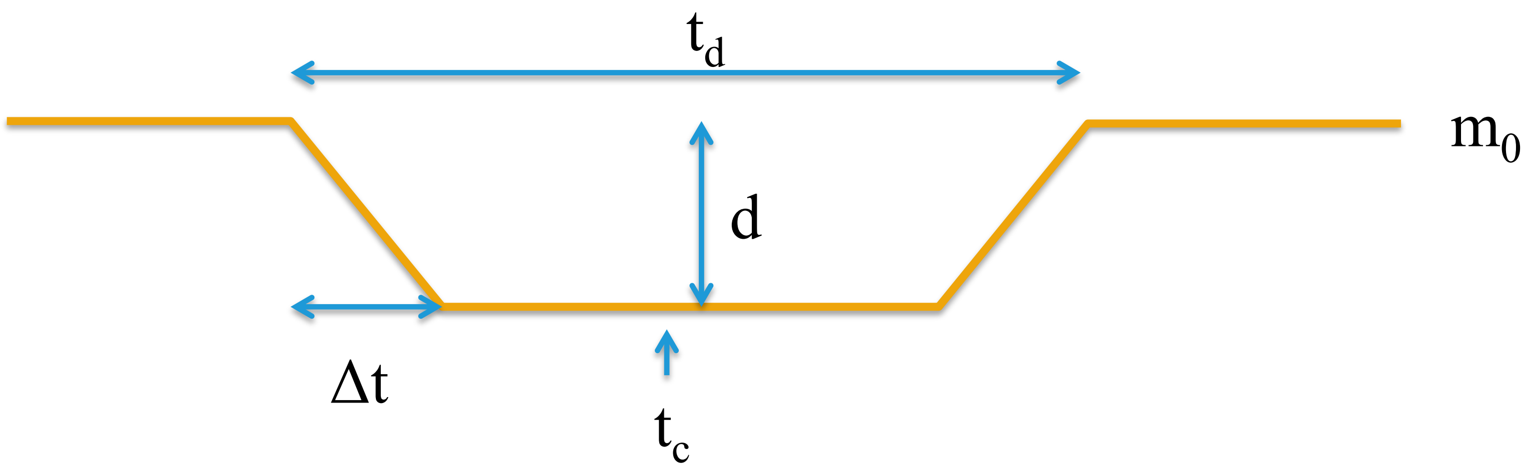


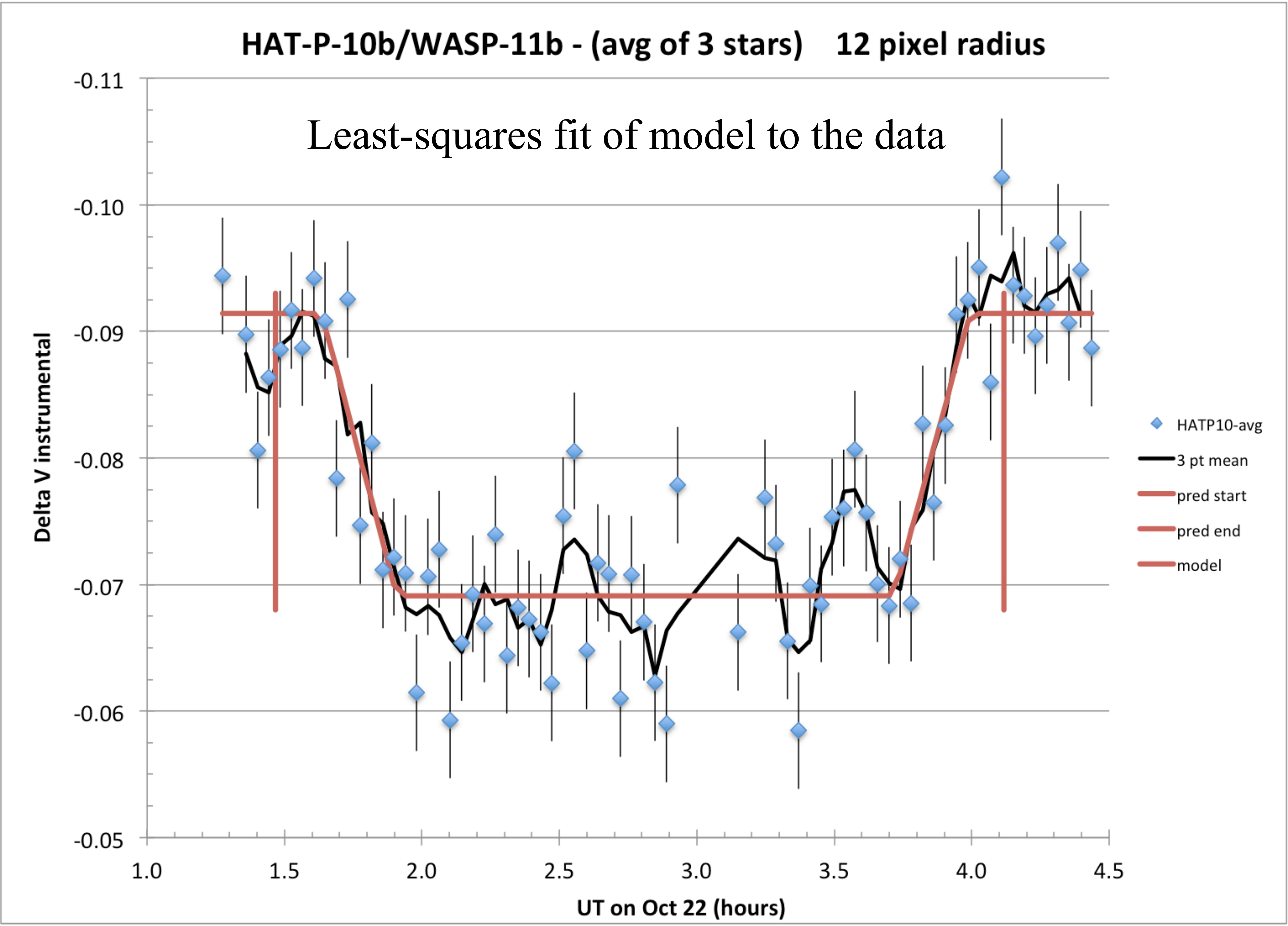


The estimated depth of 0.0223 ± 0.0015 magnitude is shallower than the 0.025 tabulated, but agrees with the results shown above (taken from the results in the Exoplanet Transit Database). Note also the shorter durations and delayed transit times.

Lab 4 Analysis

- Once you have your transit light curve, how to quantitatively estimate the depth, duration, and central time?
  - Another approach is to adopt a simple model for the transit light curve and adjust t_c, t_d, Δt, d, and m_0 (by hand or by least-squares fit) to achieve a good match to the data.




HAT-P-10b/WASP-11b - (avg of 3 stars)   12 pixel radius
Least-squares fit of model to the data
Delta V instrumental
UT on Oct 22 (hours)
-0.11
-0.10
-0.09
-0.08
-0.07
-0.06
-0.05
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
HATP10-avg
3 pt mean
pred start
pred end
model

Lab 5 Analysis

- Once you have your transit light curve, how to quantitatively estimate the depth, duration, and central time?
  - Example: t_c = 2.814 UT (2.792 predicted) ± 0.05 hr?

    t_d = 2.36 hours (2.65 predicted) ± 0.1 hr?

    d = 0.0224 mag (0.025 predicted)

    Δt = 0.275 hours

A scientific least-squares fitter (as opposed to the excel solve function) would return uncertainties for the fitted parameters.