Designing an Observing Program

M. J. Creech-Eakman

Outline

- Preliminary Considerations
- Choosing an Instrument
- Choosing Calibrators
- What Affects Data Quality?
- Can You Model the Results?
- Other Considerations
- Tools for Use
- Three Recent Examples
- Conclusions

Preliminary Considerations

- Pose a single, testable hypothesis
- Does an interferometer help you make this measurement?
- Know all necessary background information
- Know whether ancillary data are needed and if already available

Choosing an Instrument

- Primary Considerations:
  - Hemisphere – zenith angle limitations
  - Wavelengths – acquisition, tracking and science
  - Angular Resolution – wavelength/baseline dependent
  - Sensitivity
- Secondary Considerations:
  - Spectral Resolution – lines, SNR
  - UV Coverage – snapshot, long-term monitoring
  - Amplitudes and/or Phases
- Nota Bene:
  - Special Modes – e.g. nulling, phase referencing
  - Availability of Instrument – science mission, collaboration

Choosing Calibrators

- No single step is more important!

- Considerations:
  - Proximity to Science Object
  - Stability – Variable, Binary, Oblate
  - Colors/Spectral Types – Needed for AO? Instrumental response?
  - Spectral Lines – Spectral Resolution
  - Resolved or Unresolved
  - Other Considerations – Different calibrators for different parts of the science program

Calibration

- Some types of interferometric observables need different levels of fidelity than others
  - Phases – closure phase measurements more immune to calibration errors than others
  - Amplitudes – what level of V^2 errors can you suffer and still make a meaningful measurement
  - Spectral Lines – how well do they need to be known
  - Nulling – how unresolved does your source have to be to avoid leaking through
  - Phase referencing – how large is the isoplanatic angle, do the target and calibrator need to be done in the same mode

Conservative Approach to Calibration

- Pick at least 2 unresolved calibrators
- Make sure they are free of any “disturbing” references
- Make sure they are free of spectral lines and approximately the same magnitude as your target
- Pick sources as nearby as possible to the target source – interferometer dependent
- Interleave with target during observations

What Affects Data Quality?

- System Visibility – absolute and fluctuations
- Sensitivity – are you meeting it?
- Atmospheric Issues – what are your requirements on seeing and Strehl
- System Diagnostics – what do the black-belt interferometrists look at?
- Be Prepared to Make Changes in Real-Time – have a back-up program ready

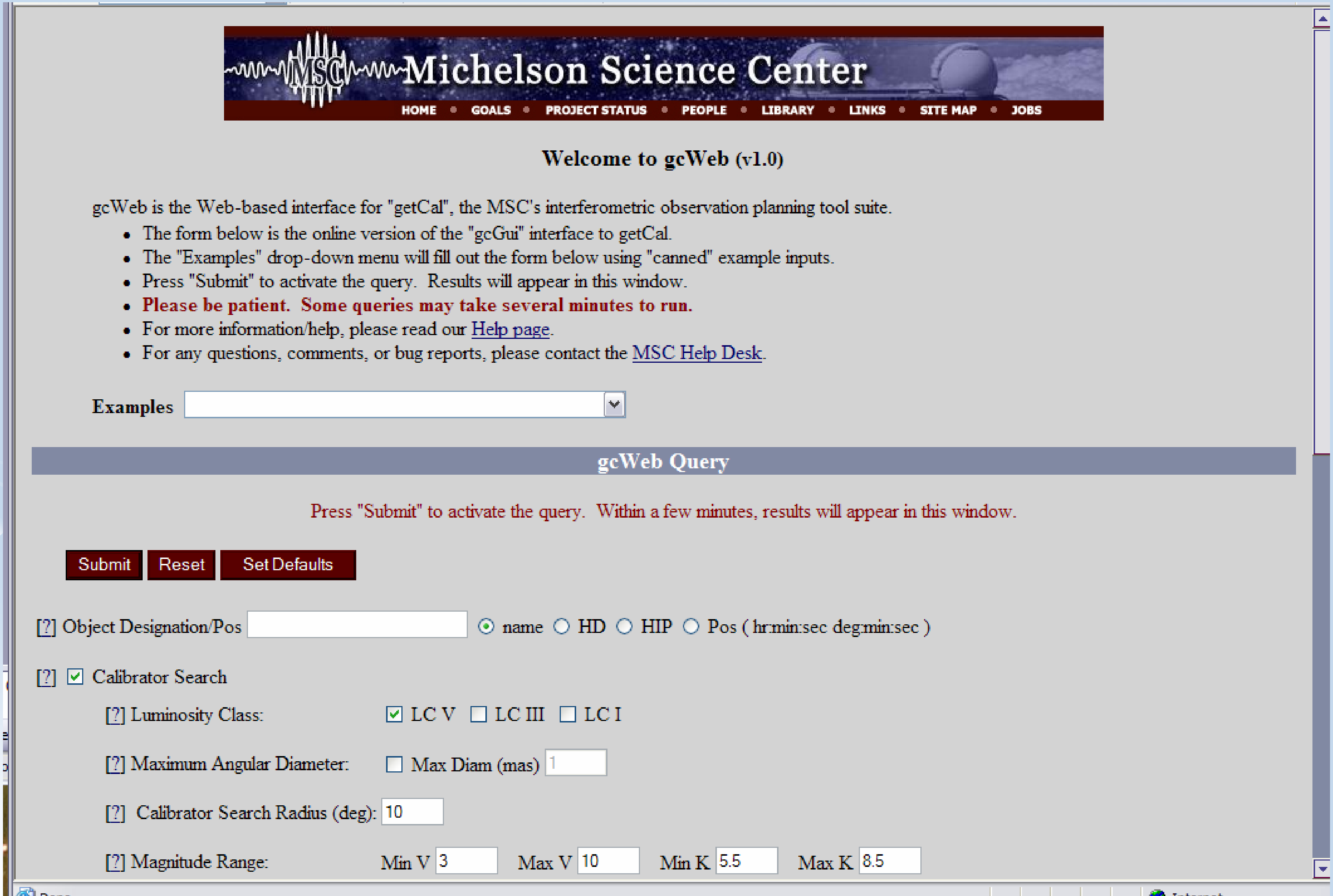
Modeling the Results

- Pre and Post Observing
  - often required by TACs
  - helps distinguish how to make the observation
  - allows you to determine key times to observe
- What Information Will You Need
  - photometry, spectroscopy, RV, ephemeredes
  - contemporaneous?, periodic?
  - parametric models
- What Resources Will You Need
  - computer time/software
  - theorist, collaborator
  - time on other telescopes

Other Considerations

- Timed programs
  - variable stars, binaries, ToO
- Long-term programs
  - slow or periodic changes in the target
  - deep integrations for sensitivity
- Coordinated programs
  - with other observatories

Tools for use



Welcome to gcWeb (v1.0)

gcWeb is the Web-based interface for "getCal", the MSC's interferometric observation planning tool suite.

- The form below is the online version of the "gcGui" interface to getCal.
- The "Examples" drop-down menu will fill out the form below using "canned" example inputs.
- Press "Submit" to activate the query. Results will appear in this window.
- **Please be patient. Some queries may take several minutes to run.**
- For more information/help, please read our Help page.
- For any questions, comments, or bug reports, please contact the MSC Help Desk.

Examples

gcWeb Query

Press "Submit" to activate the query. Within a few minutes, results will appear in this window.

[?] Object Designation/Pos ● name ○ HD ○ HIP ○ Pos (hr:min:sec deg:min:sec)

[?] ☑ Calibrator Search

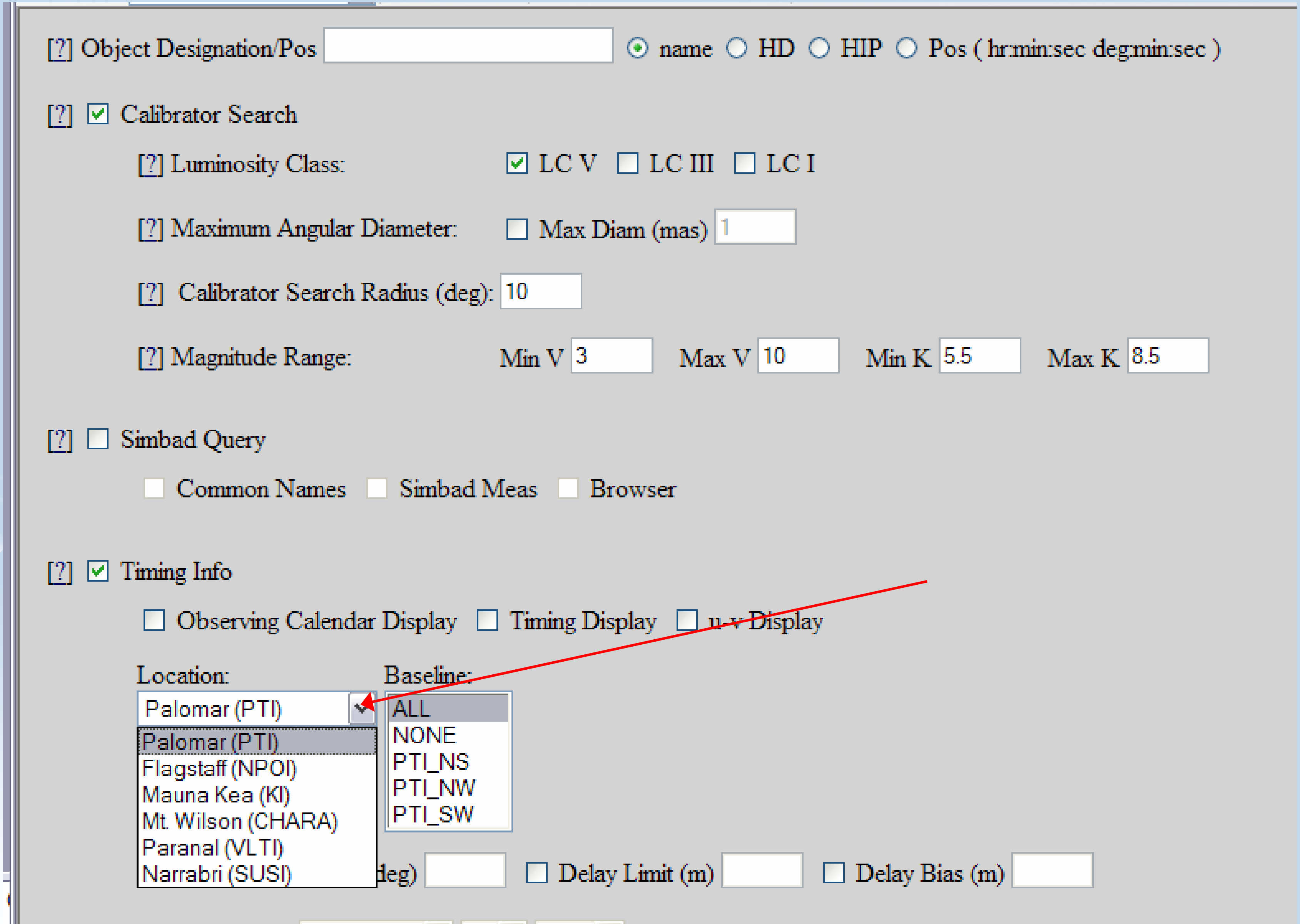
[?] Luminosity Class: ☑ LC V ☐ LC III ☐ LC I

[?] Maximum Angular Diameter: ☐ Max Diam (mas) 1

[?] Calibrator Search Radius (deg): 10

[?] Magnitude Range: Min V 3 Max V 10 Min K 5.5 Max K 8.5

Features



[?] Object Designation/Pos ● name ○ HD ○ HIP ○ Pos (hr:min:sec deg:min:sec)

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[?] ☐ Simbad Query

☐ Common Names ☐ Simbad Meas ☐ Browser

[?] ☑ Timing Info

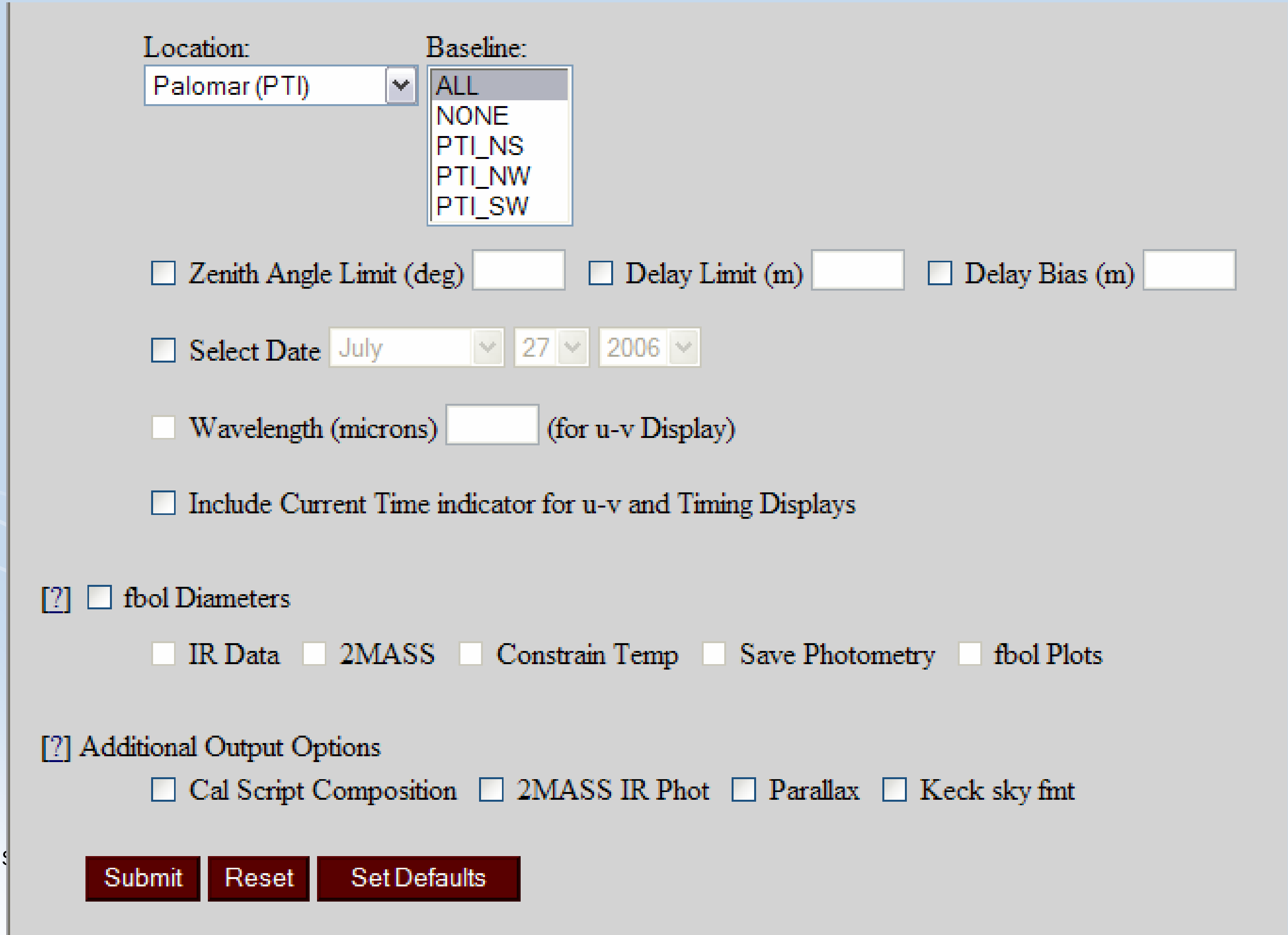
☐ Observing Calendar Display ☐ Timing Display ☐ u-v Display

Location: Palomar (PTI)

Baseline: ALL

deg) ☐ Delay Limit (m) ☐ Delay Bias (m)

Features con't



Location: Palomar (PTI)

Baseline:
- ALL
- NONE
- PTI_NS
- PTI_NW
- PTI_SW

☐ Zenith Angle Limit (deg) ☐ Delay Limit (m) ☐ Delay Bias (m)

☐ Select Date July 27 2006

☐ Wavelength (microns) (for u-v Display)

☐ Include Current Time indicator for u-v and Timing Displays

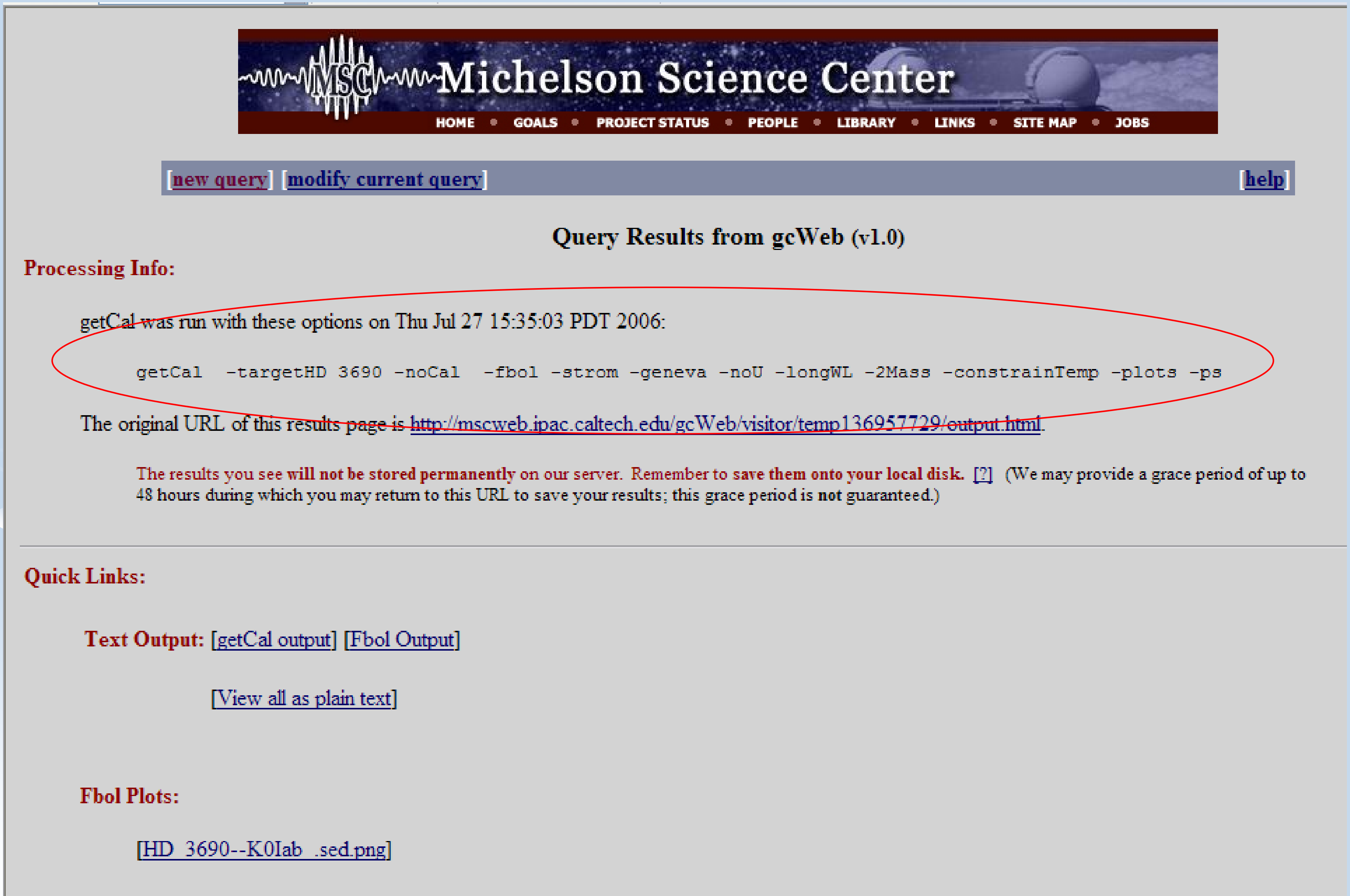
[?] ☐ fbol Diameters

☐ IR Data ☐ 2MASS ☐ Constrain Temp ☐ Save Photometry ☐ fbol Plots

[?] Additional Output Options

☐ Cal Script Composition ☐ 2MASS IR Phot ☐ Parallax ☐ Keck sky fmt

Some Outputs



Query Results from gcWeb (v1.0)

Processing Info:

getCal was run with these options on Thu Jul 27 15:35:03 PDT 2006:

```
getCal  -targetHD 3690 -noCal  -fbol -strom -geneva -noU -longWL -2Mass -constrainTemp -plots -ps
```

The original URL of this results page is http://mscweb.ipac.caltech.edu/gcWeb/visitor/temp136957729/output.html.

The results you see **will not be stored permanently** on our server. Remember to **save them onto your local disk.** [?] (We may provide a grace period of up to 48 hours during which you may return to this URL to save your results; this grace period is **not** guaranteed.)

Quick Links:

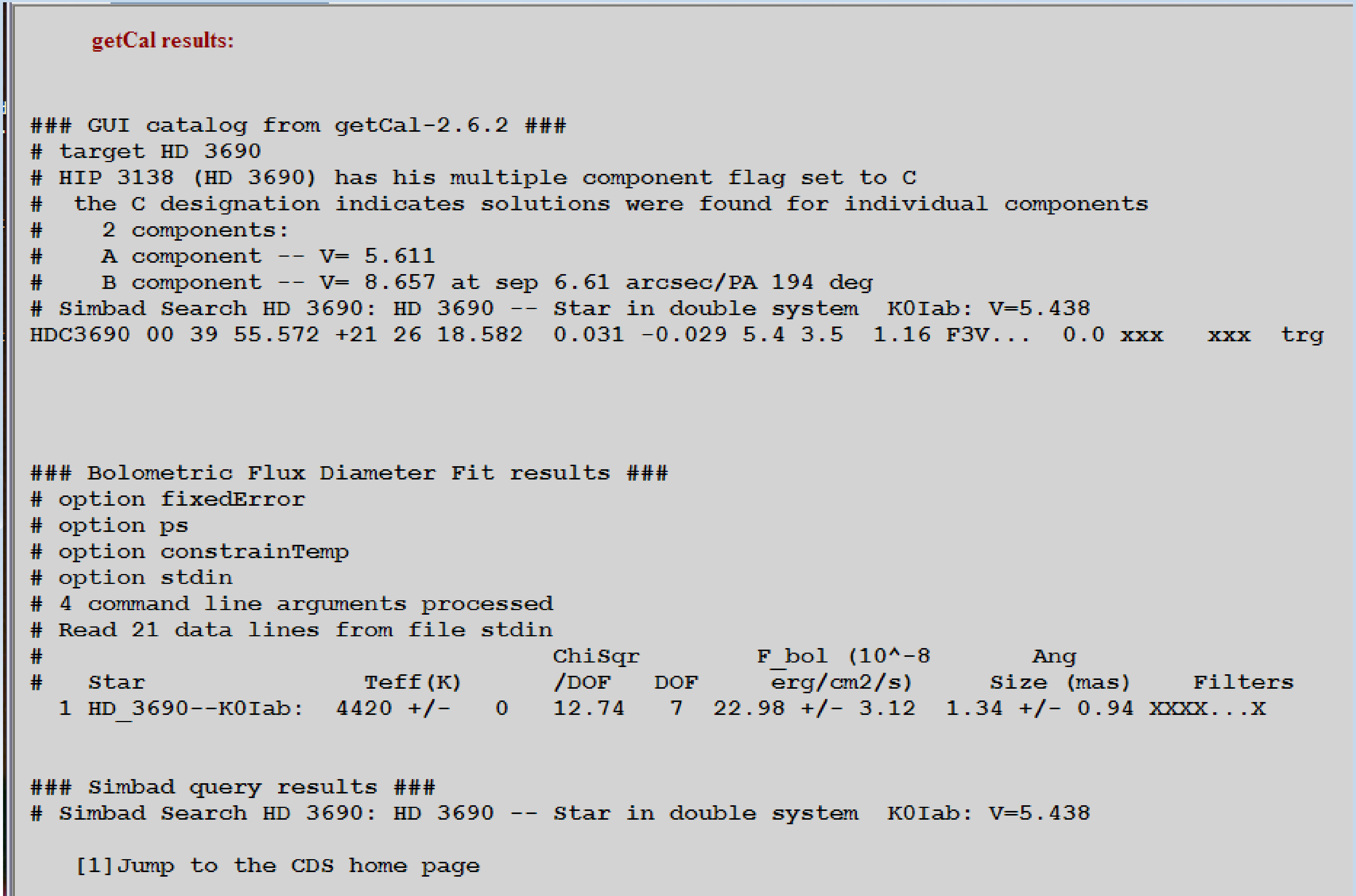
Text Output: [getCal output] [Fbol Output]

[View all as plain text]

Fbol Plots:

[HD_3690--K0Iab_.sed.png]

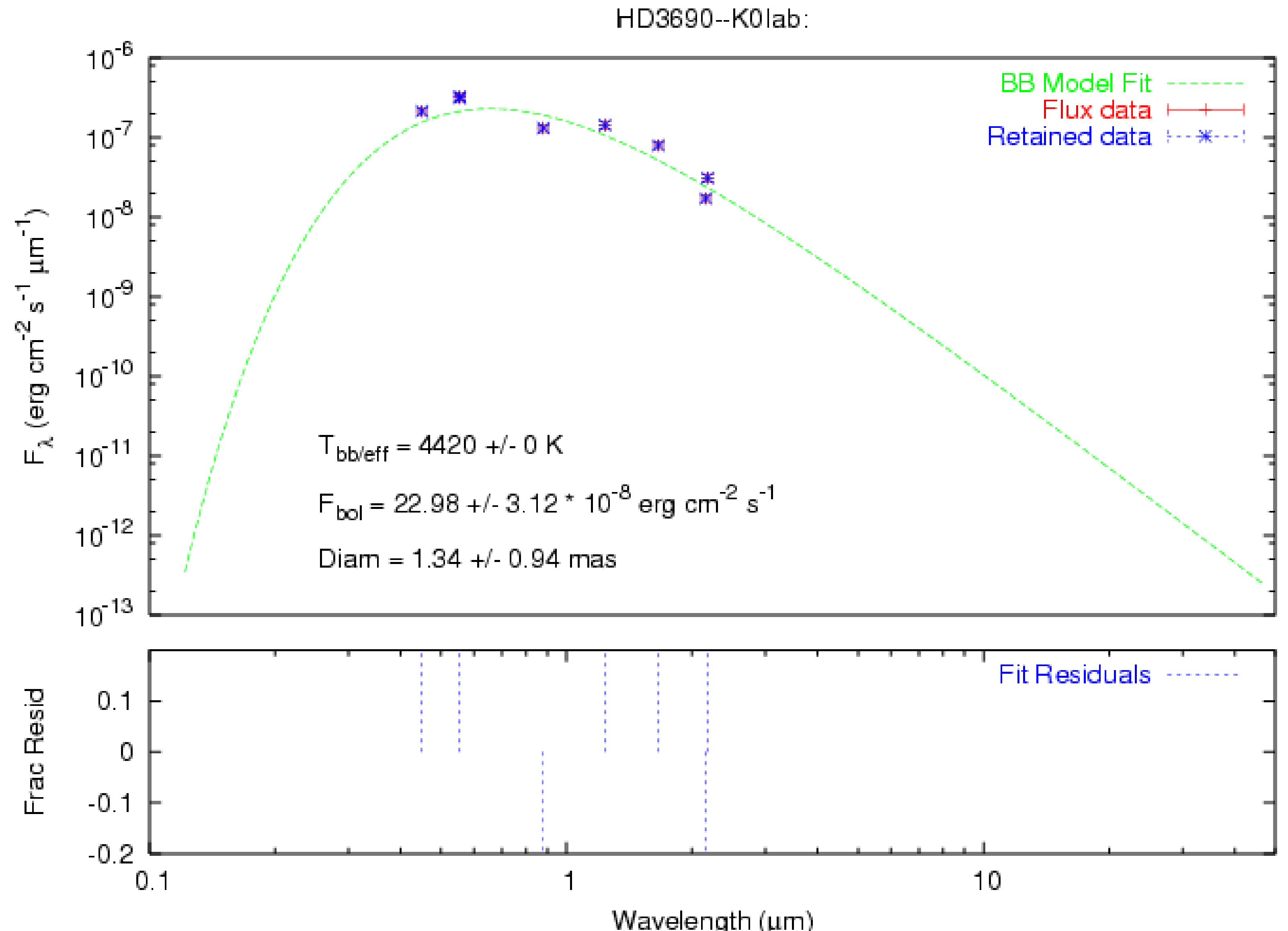
getCal Output



getCal results:

```
### GUI catalog from getCal-2.6.2 ###
# target HD 3690
# HIP 3138 (HD 3690) has his multiple component flag set to C
#  the C designation indicates solutions were found for individual components
#    2 components:
#    A component -- V= 5.611
#    B component -- V= 8.657 at sep 6.61 arcsec/PA 194 deg
# Simbad Search HD 3690: HD 3690 -- Star in double system  K0Iab: V=5.438
HDC3690 00 39 55.572 +21 26 18.582  0.031 -0.029 5.4 3.5  1.16 F3V...  0.0 xxx   xxx  trg




### Bolometric Flux Diameter Fit results ###
# option fixedError
# option ps
# option constrainTemp
# option stdin
# 4 command line arguments processed
# Read 21 data lines from file stdin
#                                   ChiSqr        F_bol (10^-8       Ang
#   Star               Teff(K)      /DOF   DOF     erg/cm2/s)     Size (mas)    Filters
  1 HD_3690--K0Iab:  4420 +/-   0   12.74   7  22.98 +/- 3.12  1.34 +/- 0.94 XXXX...X


### Simbad query results ###
# Simbad Search HD 3690: HD 3690 -- Star in double system  K0Iab: V=5.438

   [1]Jump to the CDS home page
```

Fbol output (i)

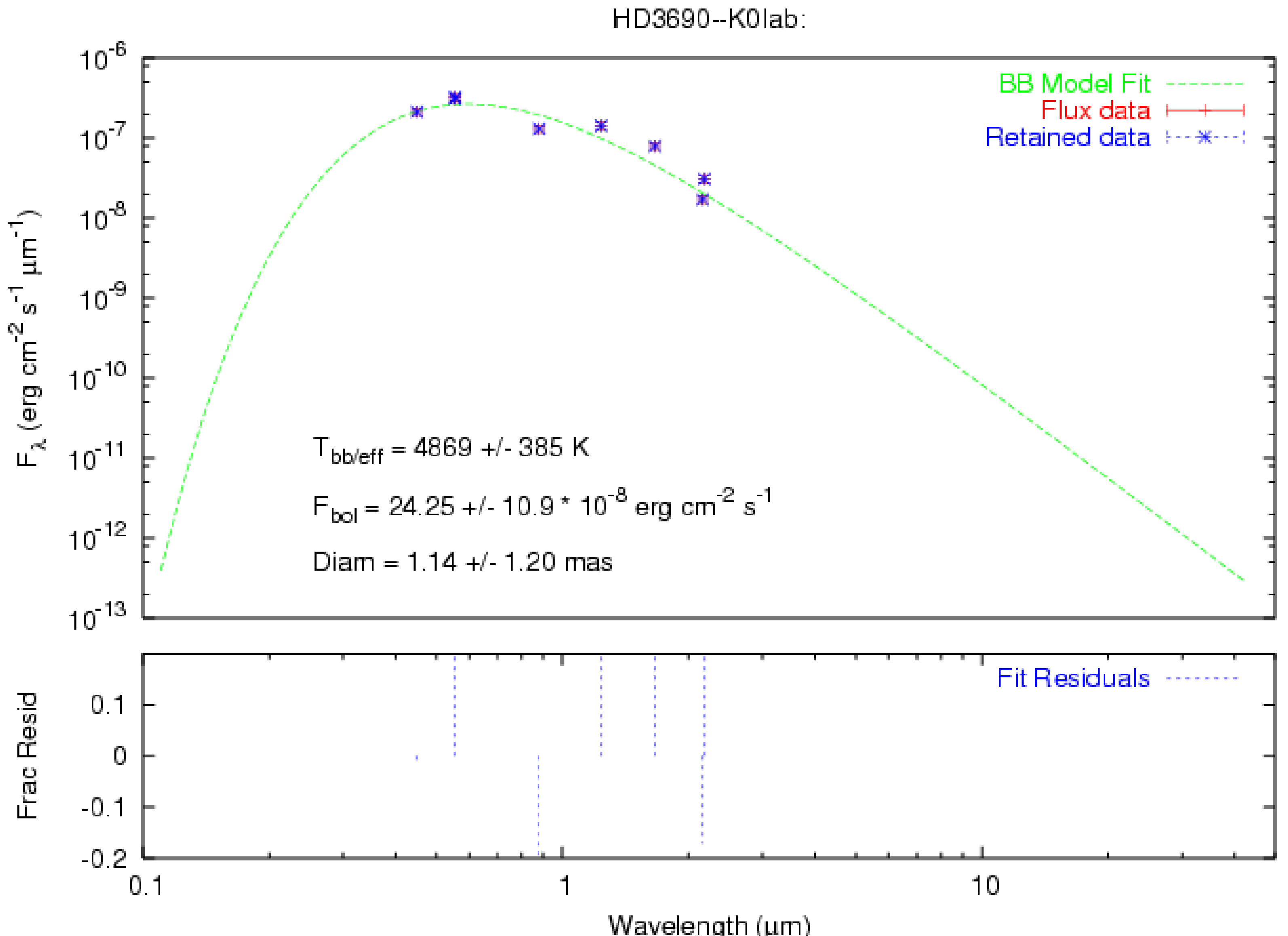


$T_{bb/eff}$ = 4420 +/- 0 K

F_{bol} = 22.98 +/- 3.12 * 10^{-8} erg cm^{-2} s^{-1}

Diam = 1.34 +/- 0.94 mas

Fbol output (ii)



HD3690--K0Iab:

$T_{bb/eff}$ = 4869 +/- 385 K

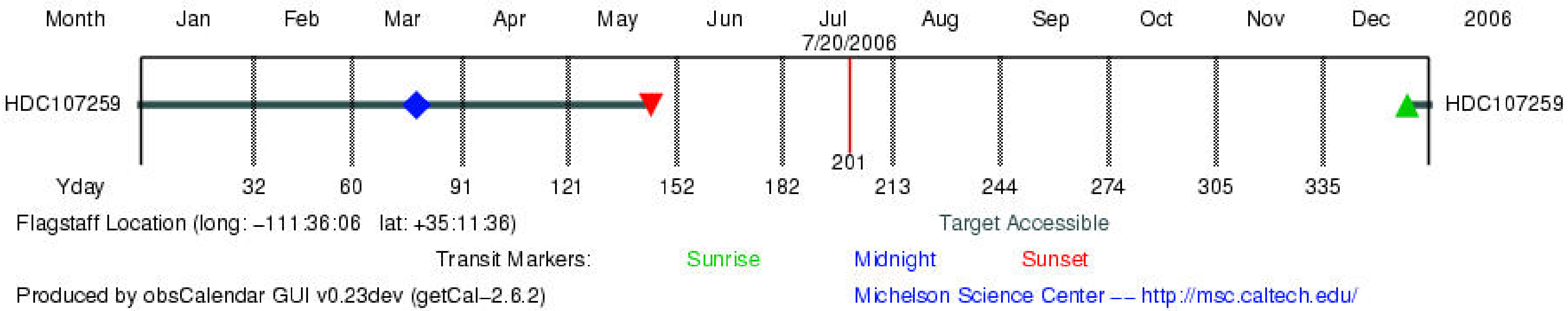
F_{bol} = 24.25 +/- 10.9 * 10^{-8} erg cm^{-2} s^{-1}

Diam = 1.14 +/- 1.20 mas

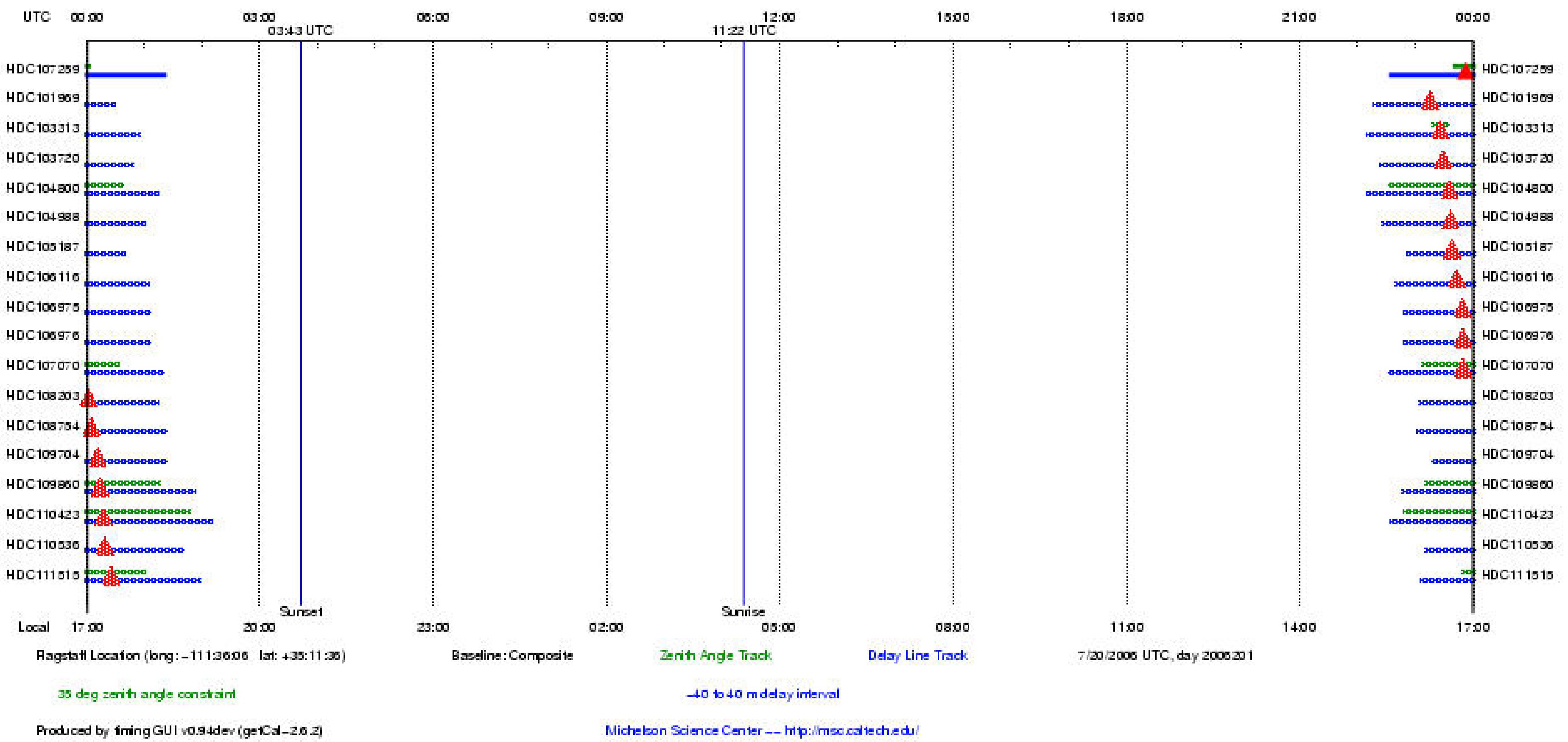
Example Number 1

- Triple System – Hummel et al., 2003, AJ
  - Hypothesis: Angular momentum axes of the smaller and larger orbits are aligned
  - Instrumental choice: Long-term coverage on a system with RV data where we'd like to get closure phases → NPOI

When can I observe?

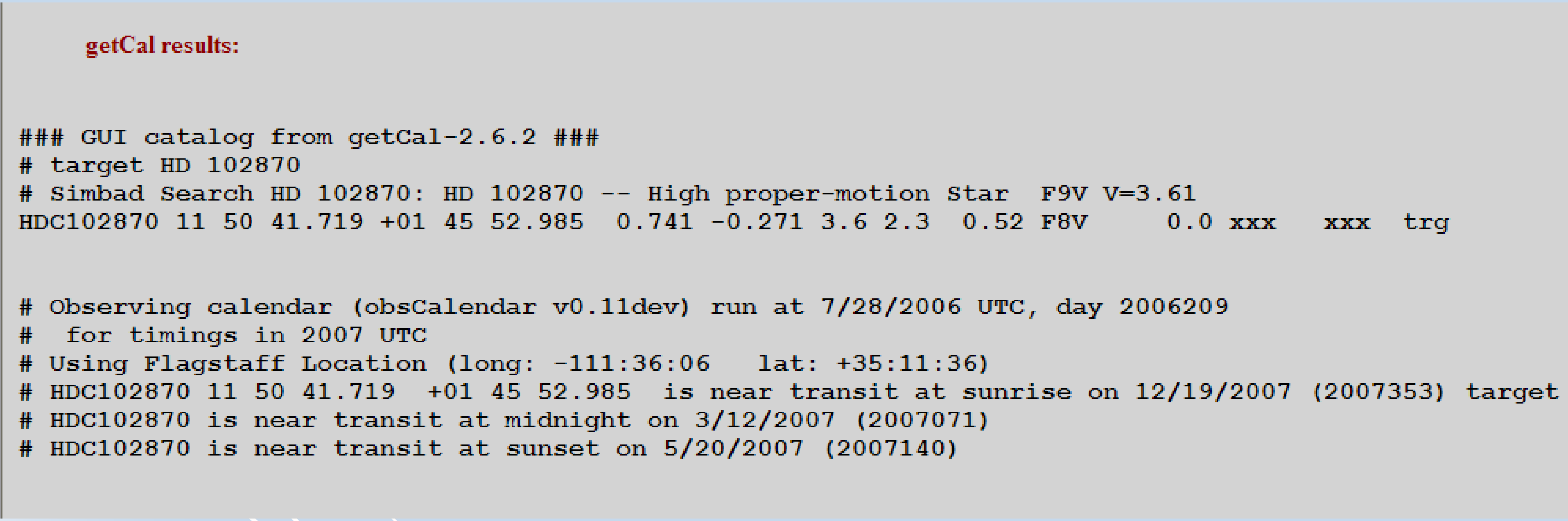


Calibrators?



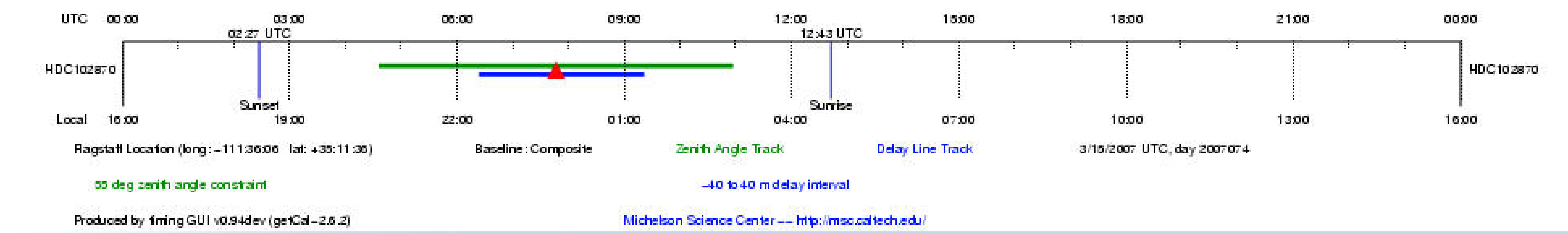
Which calibrators were used?

HD 102870 (F9V) & HD 118098 (A3V)

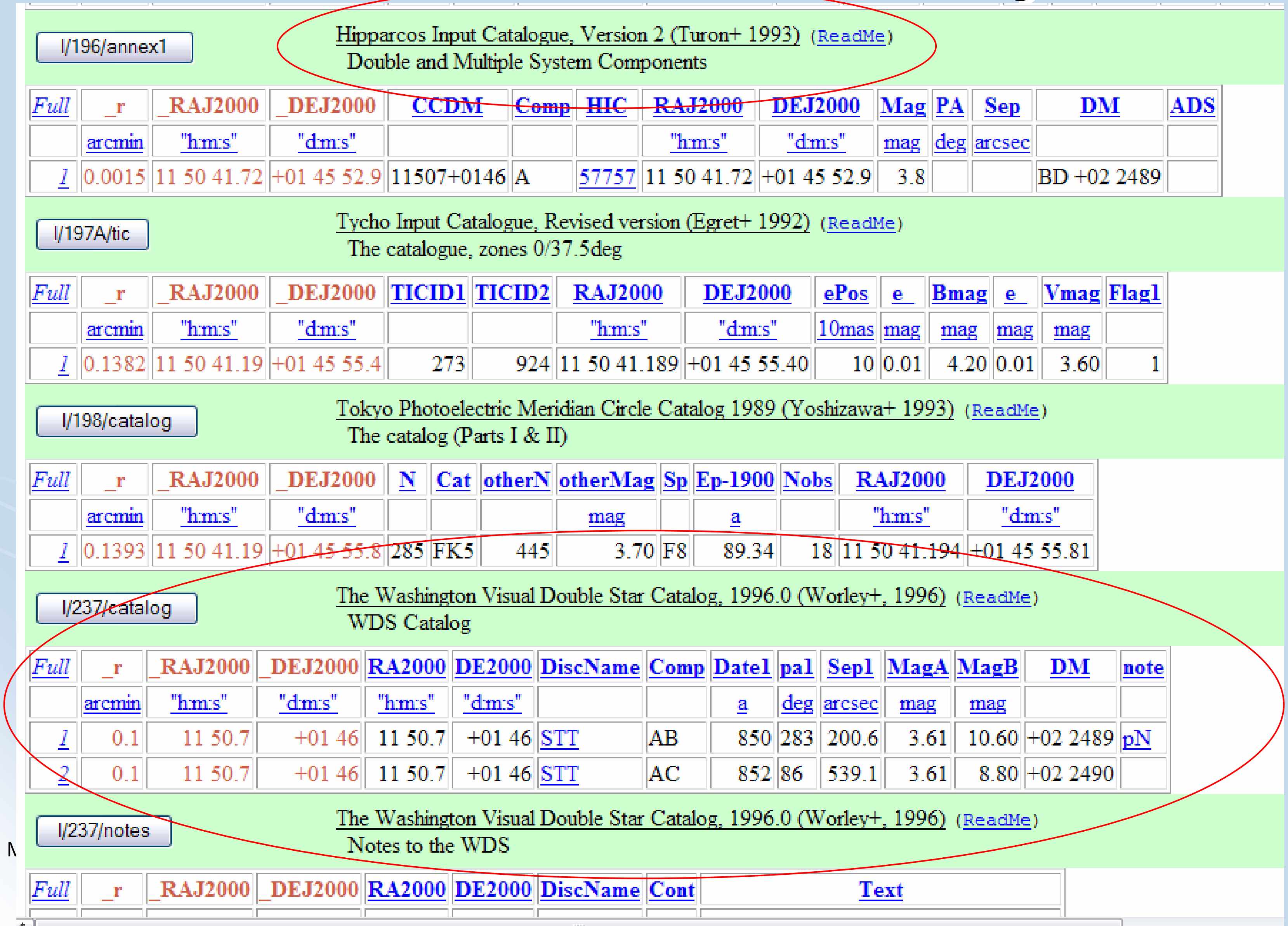


getCal results:

```
### GUI catalog from getCal-2.6.2 ###
# target HD 102870
# Simbad Search HD 102870: HD 102870 -- High proper-motion Star  F9V V=3.61
HDC102870 11 50 41.719 +01 45 52.985  0.741 -0.271 3.6 2.3  0.52 F8V     0.0 xxx   xxx  trg


# Observing calendar (obsCalendar v0.11dev) run at 7/28/2006 UTC, day 2006209
#  for timings in 2007 UTC
# Using Flagstaff Location (long: -111:36:06   lat: +35:11:36)
# HDC102870 11 50 41.719  +01 45 52.985  is near transit at sunrise on 12/19/2007 (2007353) target
# HDC102870 is near transit at midnight on 3/12/2007 (2007071)
# HDC102870 is near transit at sunset on 5/20/2007 (2007140)
```



Is the calibrator okay?



I/196/annex1

Hipparcos Input Catalogue, Version 2 (Turon+ 1993) (ReadMe)
Double and Multiple System Components

Full	_r	_RAJ2000	_DEJ2000	CCDM	Comp	HIC	RAJ2000	DEJ2000	Mag	PA	Sep	DM	ADS
	arcmin	"h:m:s"	"d:m:s"				"h:m:s"	"d:m:s"	mag	deg	arcsec		
1	0.0015	11 50 41.72	+01 45 52.9	11507+0146	A	57757	11 50 41.72	+01 45 52.9	3.8			BD +02 2489	

I/197A/tic

Tycho Input Catalogue, Revised version (Egret+ 1992) (ReadMe)
The catalogue, zones 0/37.5deg

Full	_r	_RAJ2000	_DEJ2000	TICID1	TICID2	RAJ2000	DEJ2000	ePos	e_	Bmag	e_	Vmag	Flag1
	arcmin	"h:m:s"	"d:m:s"			"h:m:s"	"d:m:s"	10mas	mag	mag	mag	mag	
1	0.1382	11 50 41.19	+01 45 55.4	273	924	11 50 41.189	+01 45 55.40	10	0.01	4.20	0.01	3.60	1

I/198/catalog

Tokyo Photoelectric Meridian Circle Catalog 1989 (Yoshizawa+ 1993) (ReadMe)
The catalog (Parts I & II)

Full	_r	_RAJ2000	_DEJ2000	N	Cat	otherN	otherMag	Sp	Ep-1900	Nobs	RAJ2000	DEJ2000
	arcmin	"h:m:s"	"d:m:s"				mag		a		"h:m:s"	"d:m:s"
1	0.1393	11 50 41.19	+01 45 55.8	285	FK5	445	3.70	F8	89.34	18	11 50 41.194	+01 45 55.81

I/237/catalog

The Washington Visual Double Star Catalog, 1996.0 (Worley+, 1996) (ReadMe)
WDS Catalog

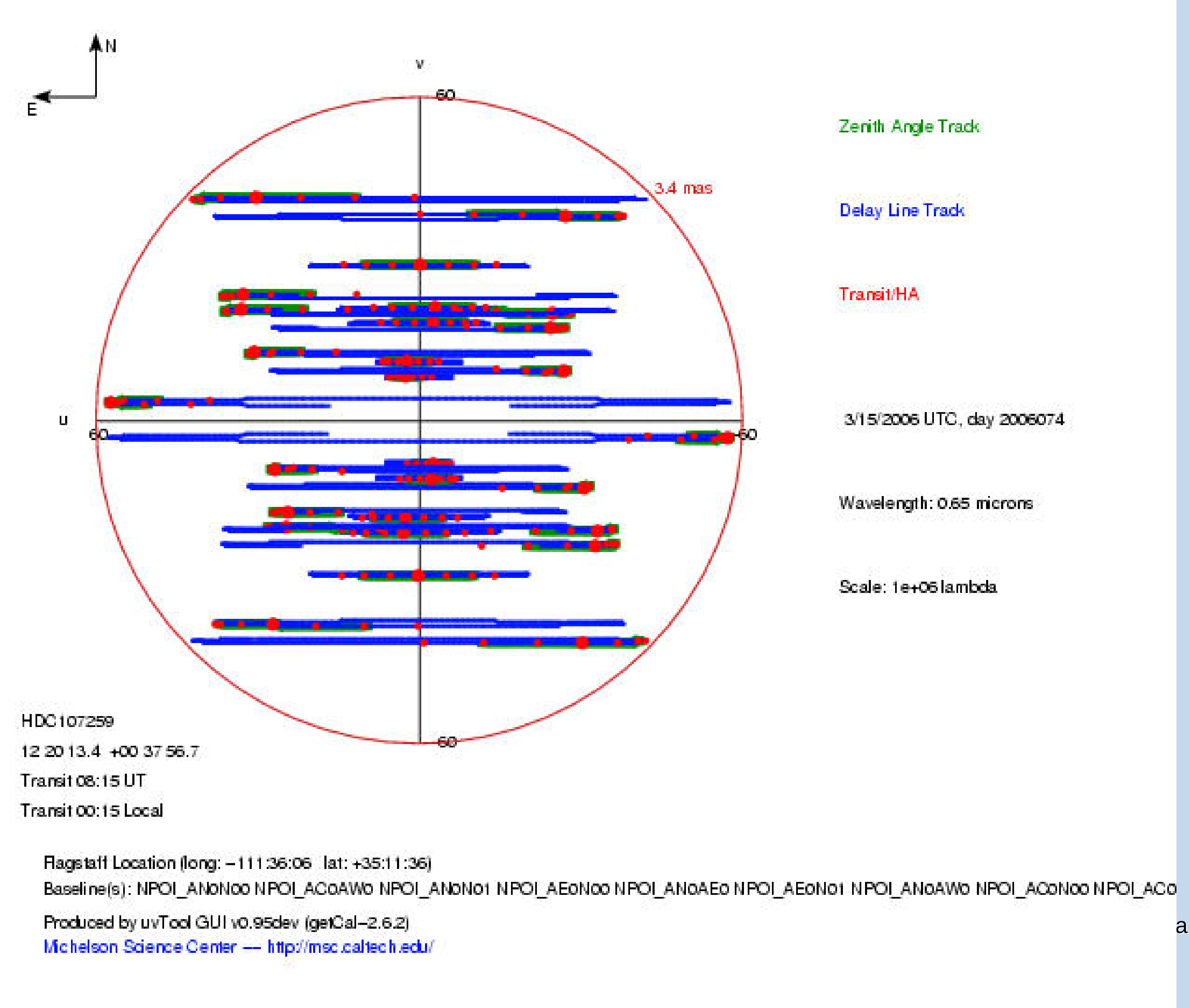
Full	_r	_RAJ2000	_DEJ2000	RA2000	DE2000	DiscName	Comp	Date1	pa1	Sep1	MagA	MagB	DM	note
	arcmin	"h:m:s"	"d:m:s"	"h:m:s"	"d:m:s"			a	deg	arcsec	mag	mag		
1	0.1	11 50.7	+01 46	11 50.7	+01 46	STT	AB	850	283	200.6	3.61	10.60	+02 2489	pN
2	0.1	11 50.7	+01 46	11 50.7	+01 46	STT	AC	852	86	539.1	3.61	8.80	+02 2490	

I/237/notes

The Washington Visual Double Star Catalog, 1996.0 (Worley+, 1996) (ReadMe)
Notes to the WDS

Full	_r	_RAJ2000	_DEJ2000	RA2000	DE2000	DiscName	Cont	Text

UV Coverage



3/15/2006 UTC, day 2006074

Wavelength: 0.65 microns

Scale: 1e+06 lambda

HDC107259

12 20 13.4 +00 37 56.7

Transit 08:15 UT

Transit 00:15 Local

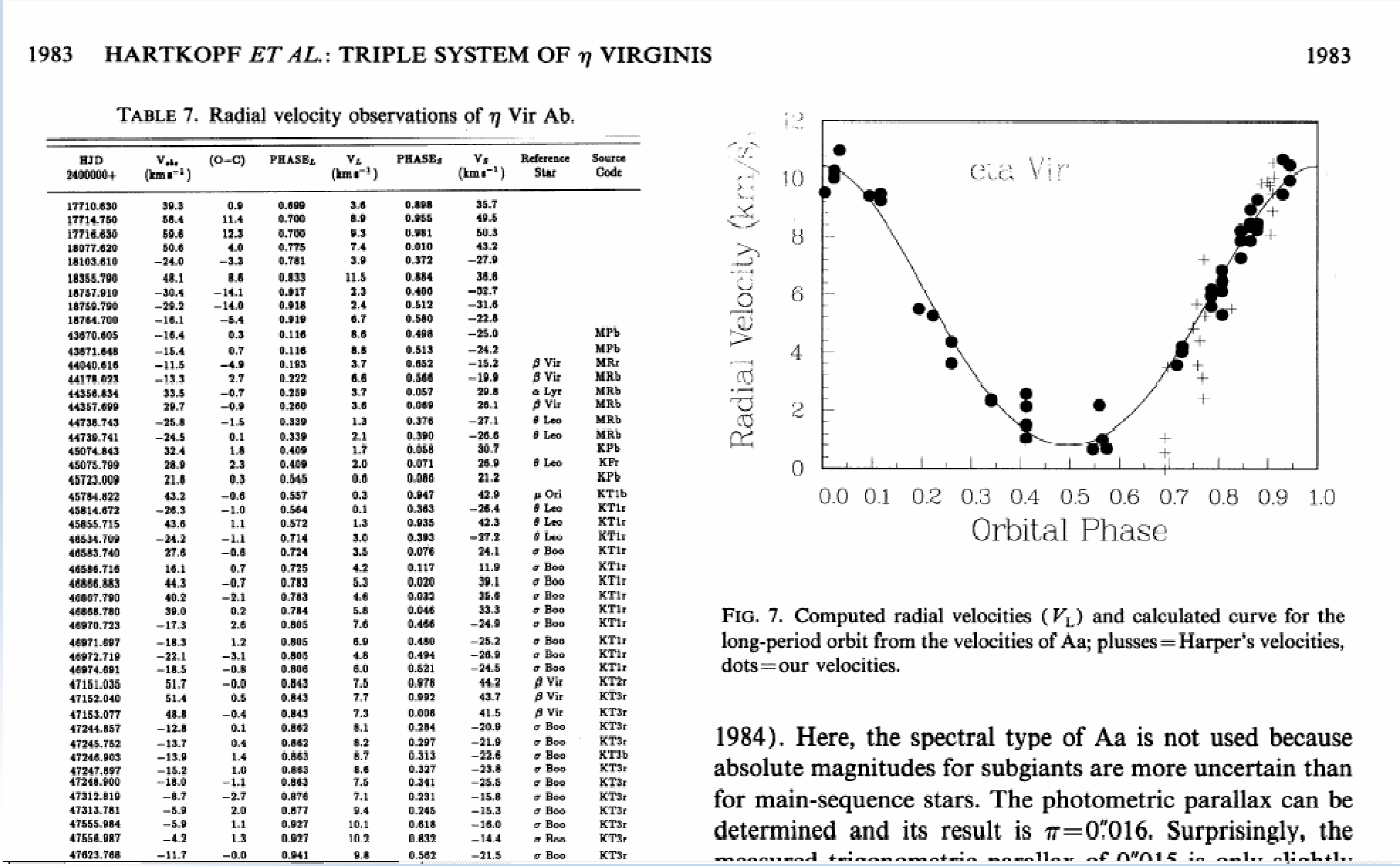
Flagstaff Location (long: −111:36:06 lat: +35:11:36)

Baseline(s): NPOI_ANoNoo NPOI_ACoAWo NPOI_ANoNo1 NPOI_AEoNoo NPOI_ANoAEo NPOI_AEoNo1 NPOI_ANoAWo NPOI_ACoNoo NPOI_ACo

Produced by uvTool GUI v0.95dev (getCal−2.6.2)

Michelson Science Center — http://msc.caltech.edu/

RV? - Yes!



1983 HARTKOPF *ET AL.*: TRIPLE SYSTEM OF η VIRGINIS 1983

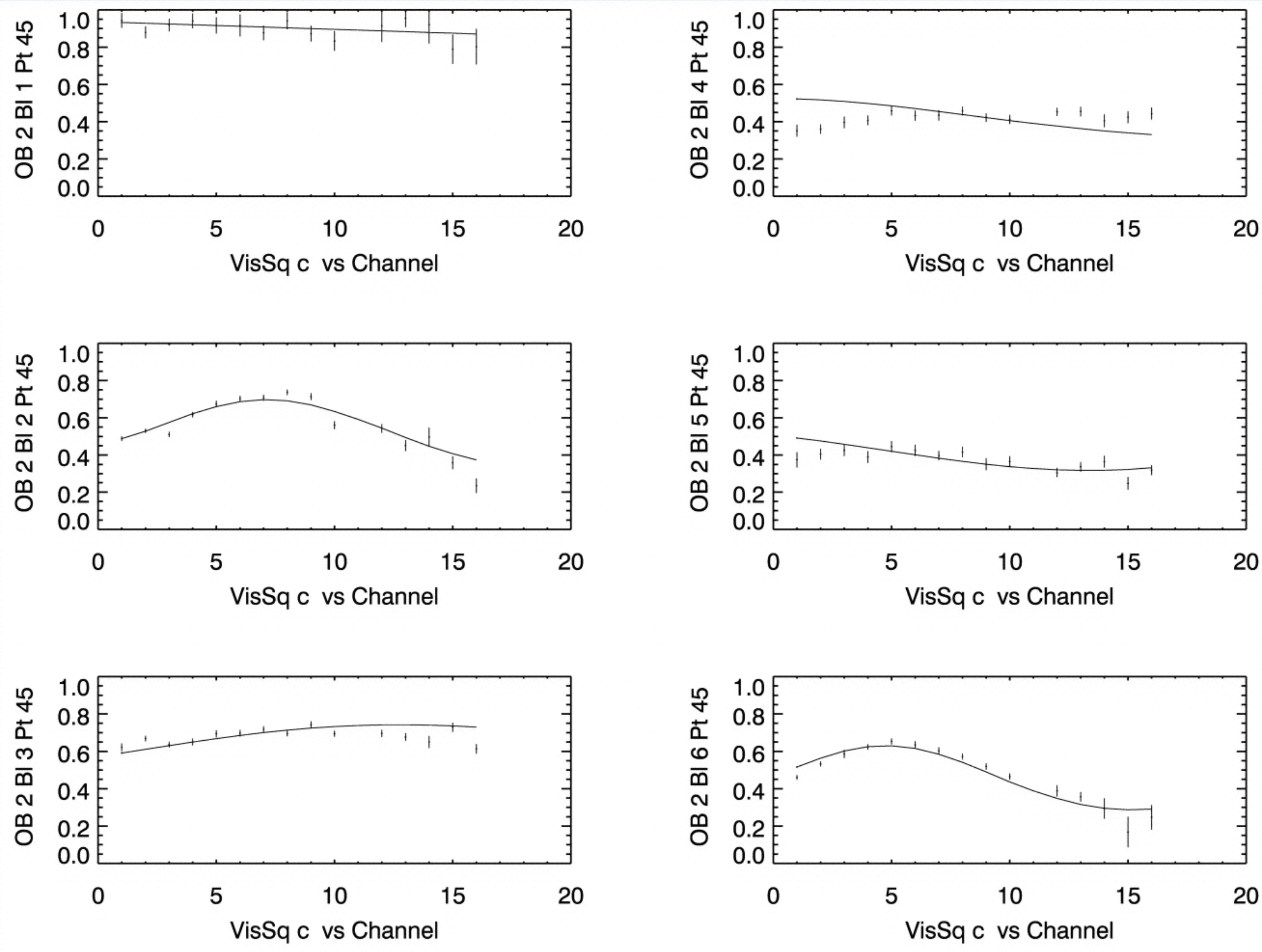
TABLE 7. Radial velocity observations of η Vir Ab.

HJD 2400000+	V_{obs} (km s^{-1})	(O−C)	PHASE$_L$	V_L (km s^{-1})	PHASE$_S$	V_S (km s^{-1})	Reference Star	Source Code
17710.630	39.3	0.9	0.699	3.6	0.898	35.7		
17714.750	58.4	11.4	0.700	8.9	0.955	49.5		
17716.630	59.6	12.3	0.700	9.3	0.981	50.3		
18077.620	50.6	4.0	0.775	7.4	0.010	43.2		
18103.610	−24.0	−3.3	0.781	3.9	0.372	−27.9		
18355.790	48.1	8.6	0.833	11.5	0.884	38.6		
18757.910	−30.4	−14.1	0.917	2.3	0.400	−32.7		
18759.790	−29.2	−14.0	0.918	2.4	0.512	−31.6		
18764.700	−16.1	−5.4	0.919	6.7	0.580	−22.8		
43670.605	−16.4	0.3	0.116	8.6	0.498	−25.0		MPb
43671.648	−15.4	0.7	0.116	8.8	0.513	−24.2		MPb
44040.616	−11.5	−4.9	0.193	3.7	0.652	−15.2	β Vir	MRr
44178.023	−13.3	2.7	0.222	6.6	0.566	−19.9	β Vir	MRb
44356.834	33.5	−0.7	0.259	3.7	0.057	29.8	α Lyr	MRb
44357.699	29.7	−0.9	0.260	3.6	0.069	26.1	β Vir	MRb
44738.743	−25.8	−1.5	0.339	1.3	0.376	−27.1	θ Leo	MRb
44739.741	−24.5	0.1	0.339	2.1	0.390	−26.6	θ Leo	MRb
45074.843	32.4	1.8	0.409	1.7	0.058	30.7		KPb
45075.799	28.9	2.3	0.409	2.0	0.071	26.9	θ Leo	KPr
45723.009	21.8	0.3	0.545	0.6	0.086	21.2		KPb
45784.822	43.2	−0.6	0.557	0.3	0.947	42.9	μ Ori	KT1b
45814.672	−26.3	−1.0	0.564	0.1	0.363	−26.4	θ Leo	KT1r
45855.715	43.6	1.1	0.572	1.3	0.935	42.3	θ Leo	KT1r
46534.709	−24.2	−1.1	0.714	3.0	0.393	−27.2	θ Leo	KT1r
46583.740	27.6	−0.6	0.724	3.5	0.076	24.1	σ Boo	KT1r
46586.716	16.1	0.7	0.725	4.2	0.117	11.9	σ Boo	KT1r
46866.883	44.3	−0.7	0.783	5.3	0.020	39.1	σ Boo	KT1r
46867.790	40.2	−2.1	0.783	4.6	0.032	35.6	σ Boo	KT1r
46868.780	39.0	0.2	0.784	5.8	0.046	33.3	σ Boo	KT1r
46970.723	−17.3	2.6	0.805	7.6	0.466	−24.9	σ Boo	KT1r
46971.697	−18.3	1.2	0.805	6.9	0.480	−25.2	σ Boo	KT1r
46972.719	−22.1	−3.1	0.805	4.8	0.494	−26.9	σ Boo	KT1r
46974.691	−18.5	−0.8	0.806	6.0	0.521	−24.5	σ Boo	KT1r
47151.035	51.7	−0.0	0.843	7.5	0.978	44.2	β Vir	KT2r
47152.040	51.4	0.5	0.843	7.7	0.992	43.7	β Vir	KT3r
47153.077	48.8	−0.4	0.843	7.3	0.006	41.5	β Vir	KT3r
47244.857	−12.8	0.1	0.862	8.1	0.284	−20.9	σ Boo	KT3r
47245.752	−13.7	0.4	0.862	8.2	0.297	−21.9	σ Boo	KT3r
47246.903	−13.9	1.4	0.863	8.7	0.313	−22.6	σ Boo	KT3b
47247.897	−15.2	1.0	0.863	8.6	0.327	−23.8	σ Boo	KT3r
47248.900	−18.0	−1.1	0.863	7.5	0.341	−25.5	σ Boo	KT3r
47312.819	−8.7	−2.7	0.876	7.1	0.231	−15.8	σ Boo	KT3r
47313.781	−5.9	2.0	0.877	9.4	0.245	−15.3	σ Boo	KT3r
47555.984	−5.9	1.1	0.927	10.1	0.618	−16.0	σ Boo	KT3r
47556.987	−4.2	1.3	0.927	10.2	0.632	−14.4	σ Boo	KT3r
47623.768	−11.7	−0.0	0.941	9.8	0.562	−21.5	σ Boo	KT3r

FIG. 7. Computed radial velocities (V_L) and calculated curve for the long-period orbit from the velocities of Aa; plusses = Harper's velocities, dots = our velocities.

1984). Here, the spectral type of Aa is not used because absolute magnitudes for subgiants are more uncertain than for main-sequence stars. The photometric parallax can be determined and its result is $\pi = 0''.016$. Surprisingly, the

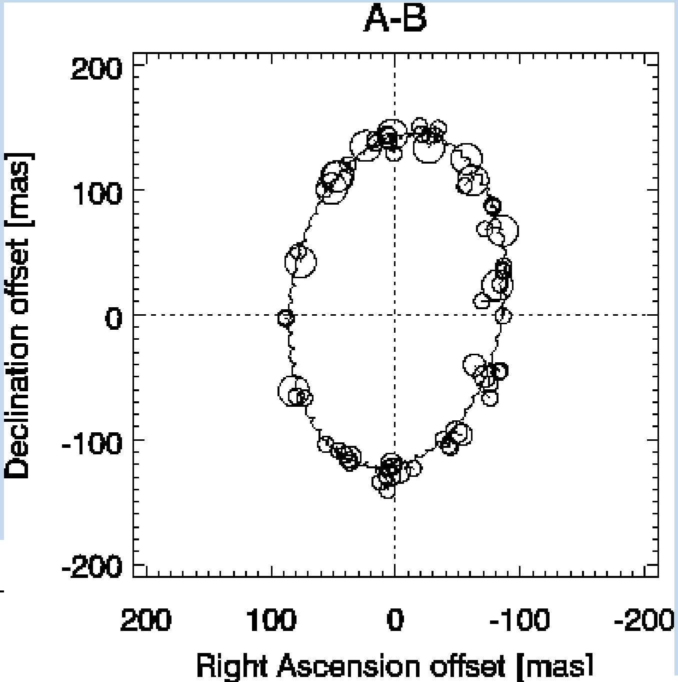
Data from Paper

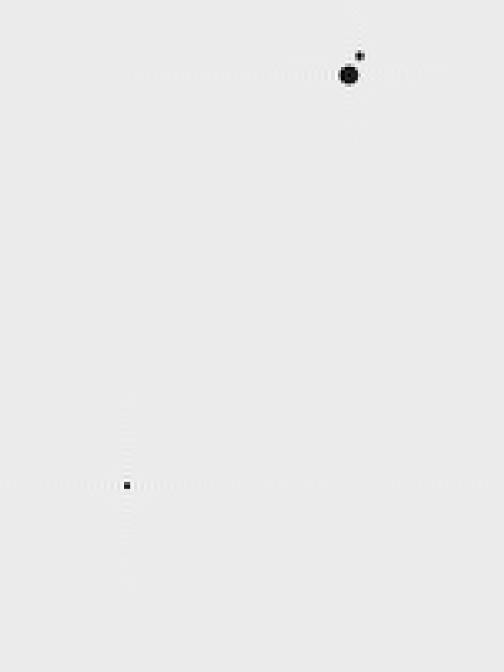


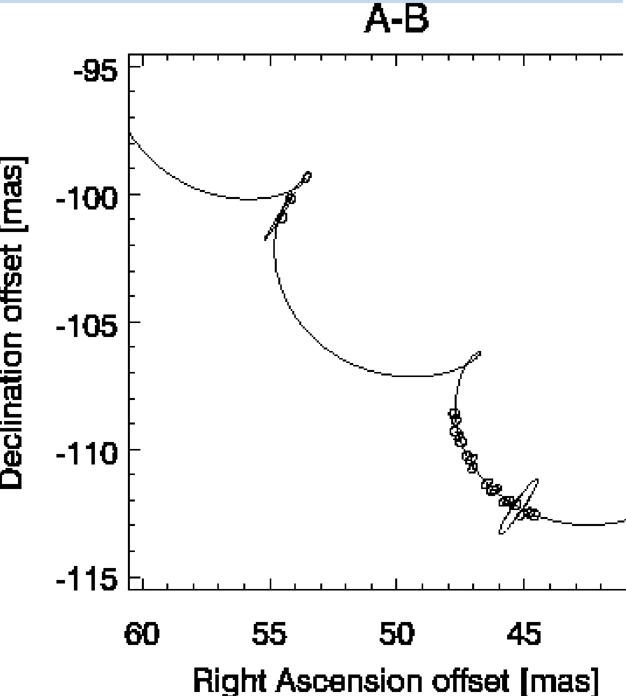
Published Results

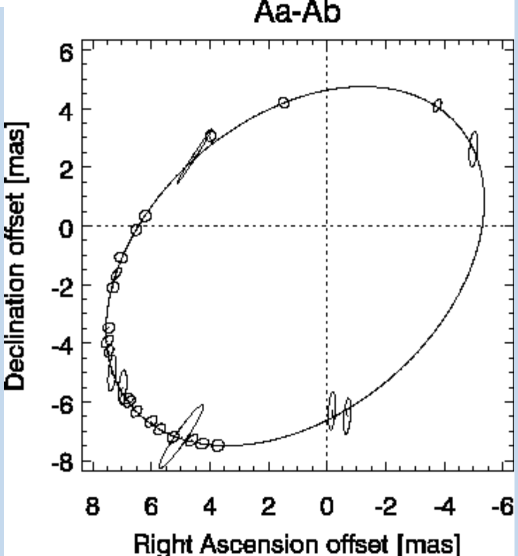
η Vir: P_{AB} = 4794d

P_{AaAb}=71d









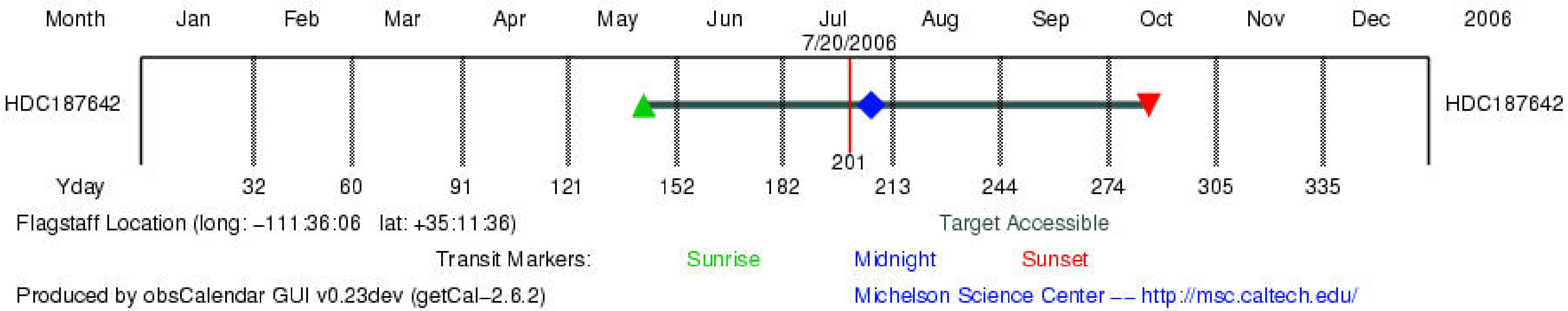
Next Steps?

- Did we answer our question?
  - derived distance, masses, relative magnitudes, orbital inclination
  - have 30.8° between orbits and orbits are co-rotating
- Is there a way to improve this experiment?
  - Do more systems…..only 22 triples have measured orbits!

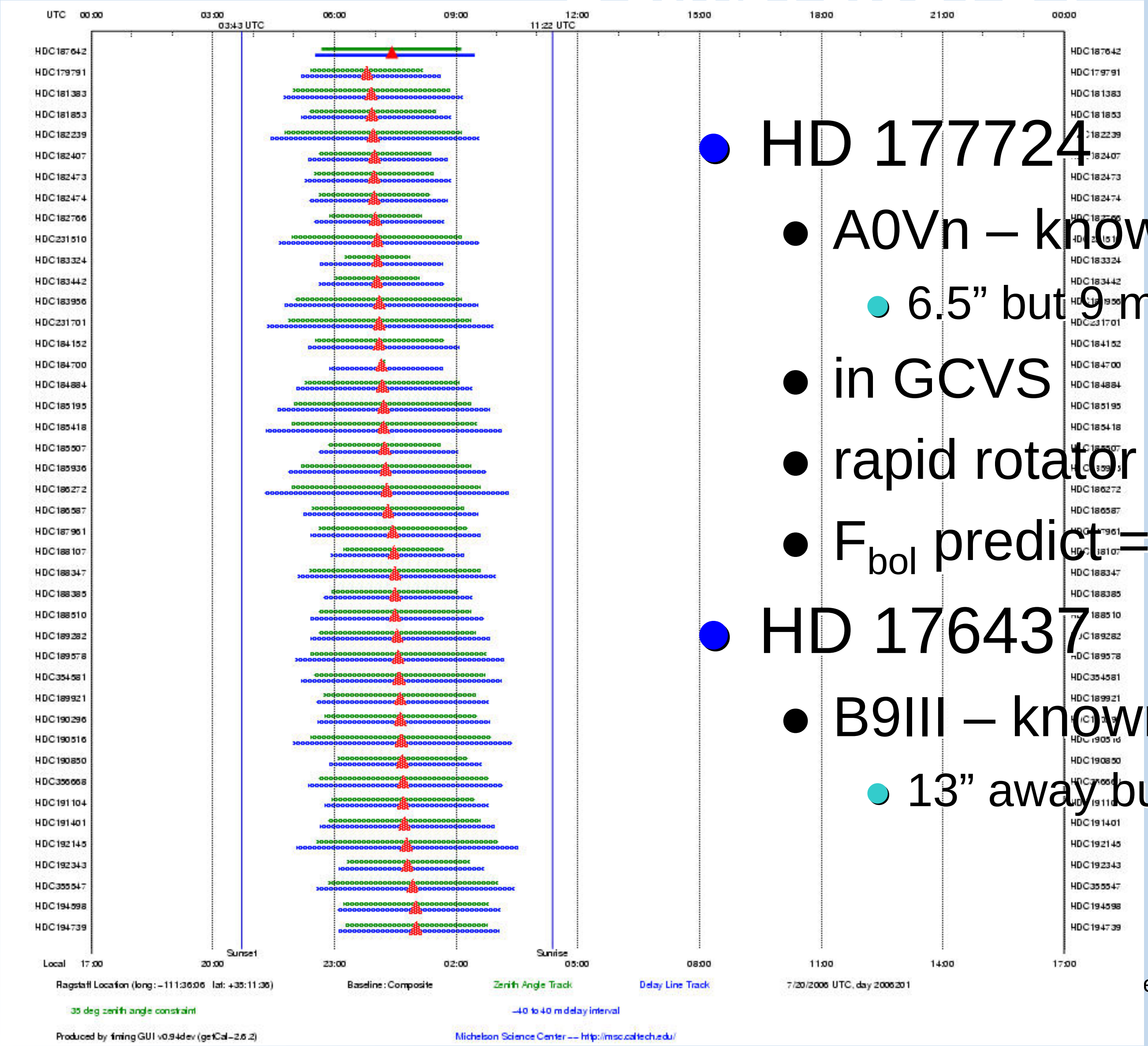
Example Number 2

- Rapidly Rotating Stars – Peterson et al, 2006, ApJ
  - Hypothesis: Rotation causes the stars to be oblate – pick Altair to test.
  - Instrumental choice: Need high angular resolution due to the differential nature of the measurement of oblateness. Probably want closure phases → NPOI.

When can I observe?

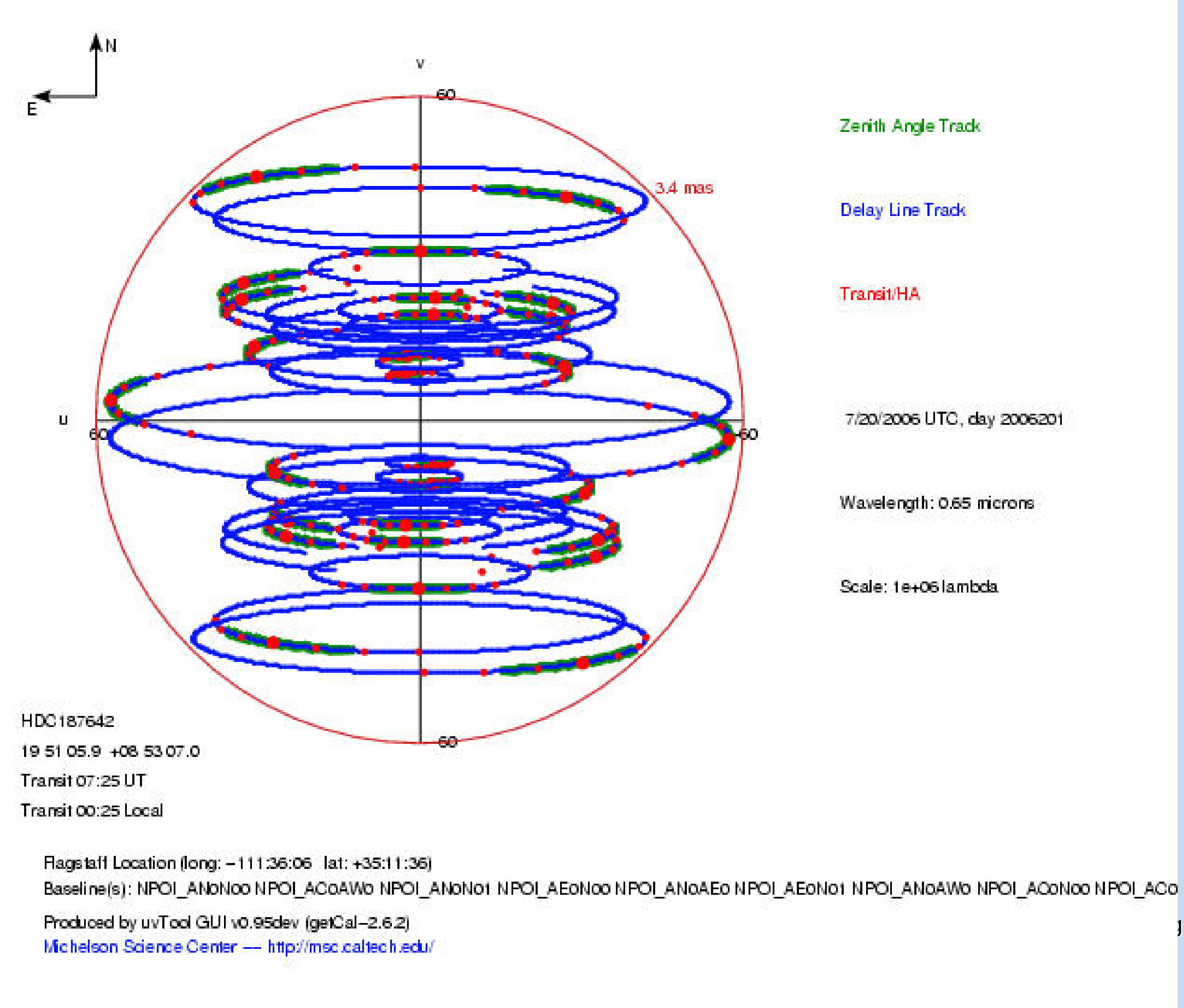


Calibrators?



- HD 177724
  - A0Vn – known double
    - 6.5” but 9 mag fainter
  - in GCVS
  - rapid rotator - ~300 km/s
  - F_{bol} predict = 0.6 +/- 0.1 mas
- HD 176437
  - B9III – known double
    - 13” away but 8.9 mag fainter

UV Coverage



7/20/2006 UTC, day 2006201

Wavelength: 0.65 microns

Scale: 1e+06 lambda

HDC187642

19 51 05.9 +08 53 07.0

Transit 07:25 UT

Transit 00:25 Local

Flagstaff Location (long: −111:36:06 lat: +35:11:36)

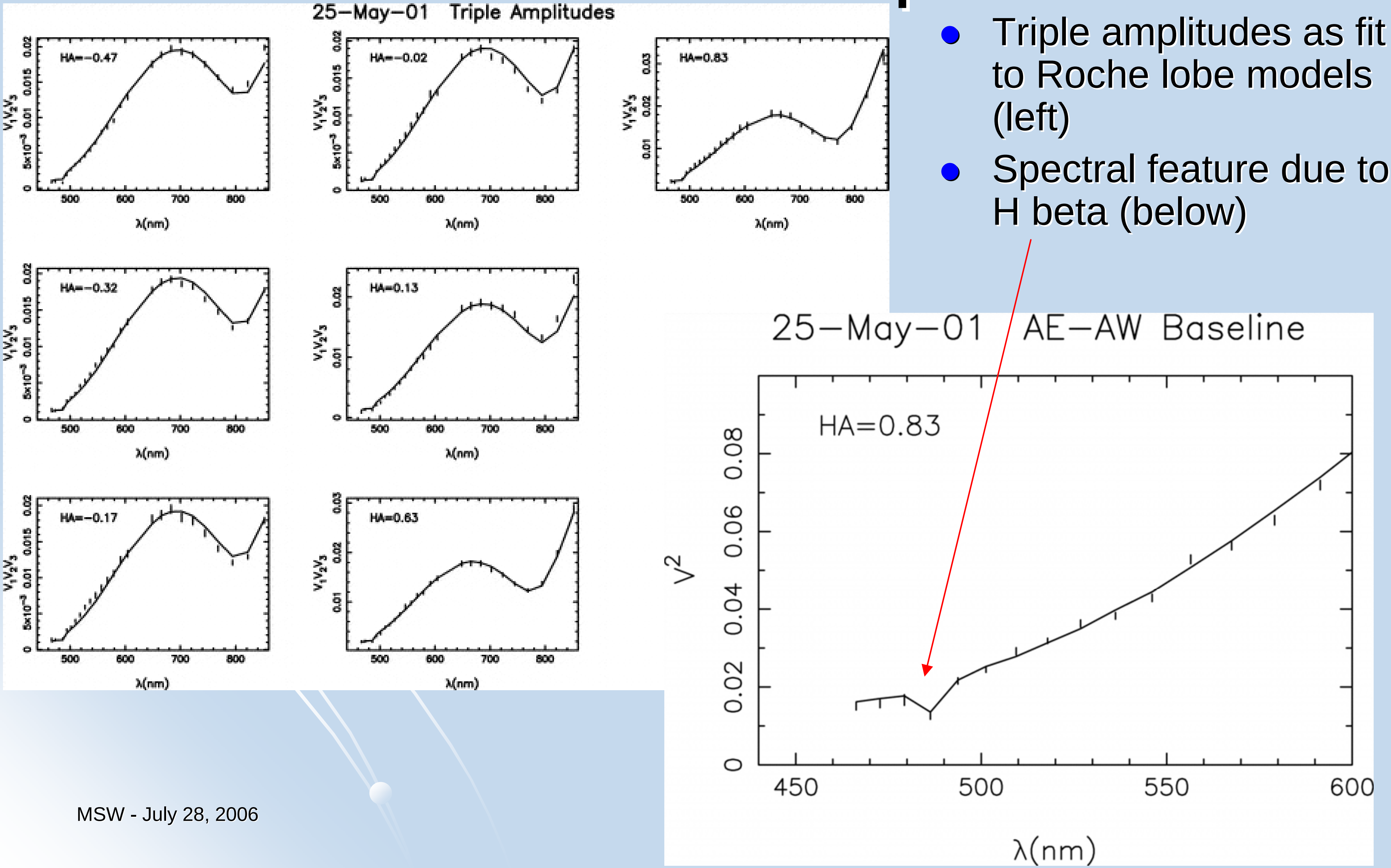
Baseline(s): NPOI_ANoNoo NPOI_ACoAWo NPOI_ANoNo1 NPOI_AEoNoo NPOI_ANoAEo NPOI_AEoNo1 NPOI_ANoAWo NPOI_ACoNoo NPOI_ACo

Produced by uvTool GUI v0.95dev (getCal−2.6.2)

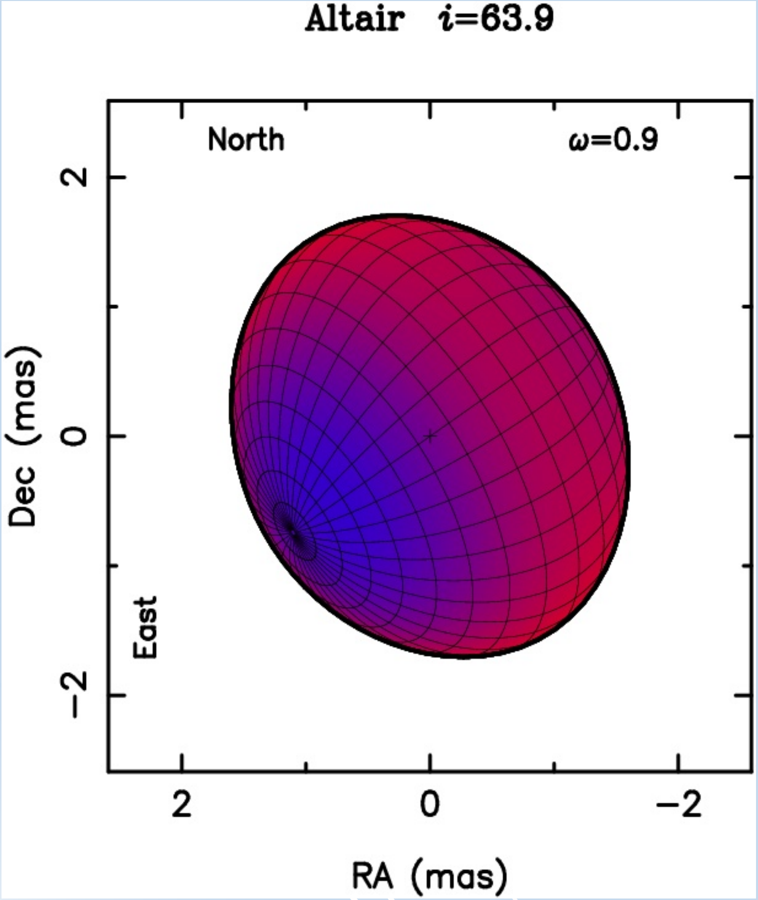
Michelson Science Center — http://msc.caltech.edu/

Data from Paper

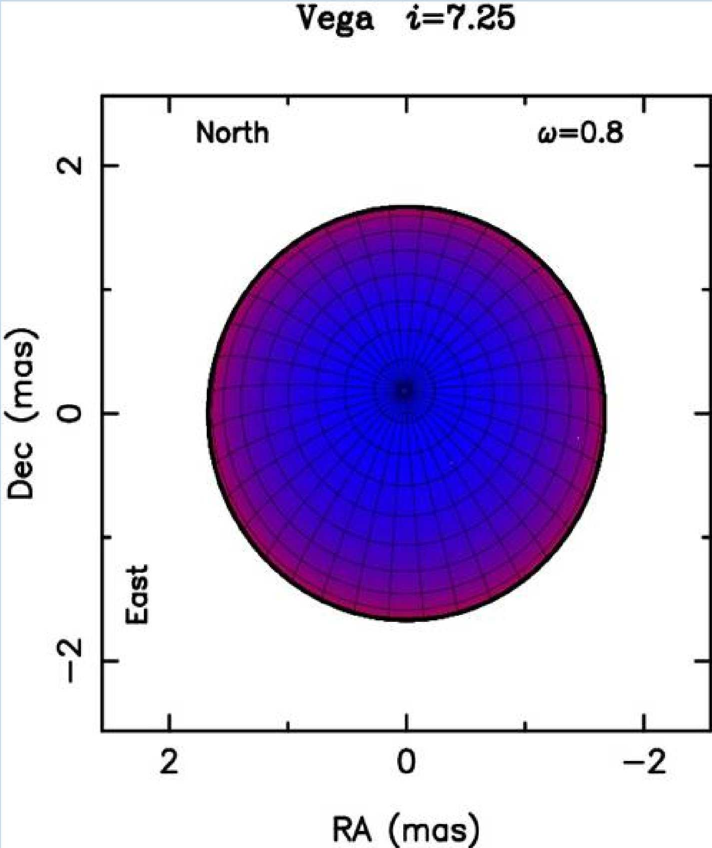
- Triple amplitudes as fit to Roche lobe models (left)
- Spectral feature due to H beta (below)



Published Results



- T_{pole} = 8740K
- T_{eq} = 6890K
- Vega from Peterson et al., 2006, Nature



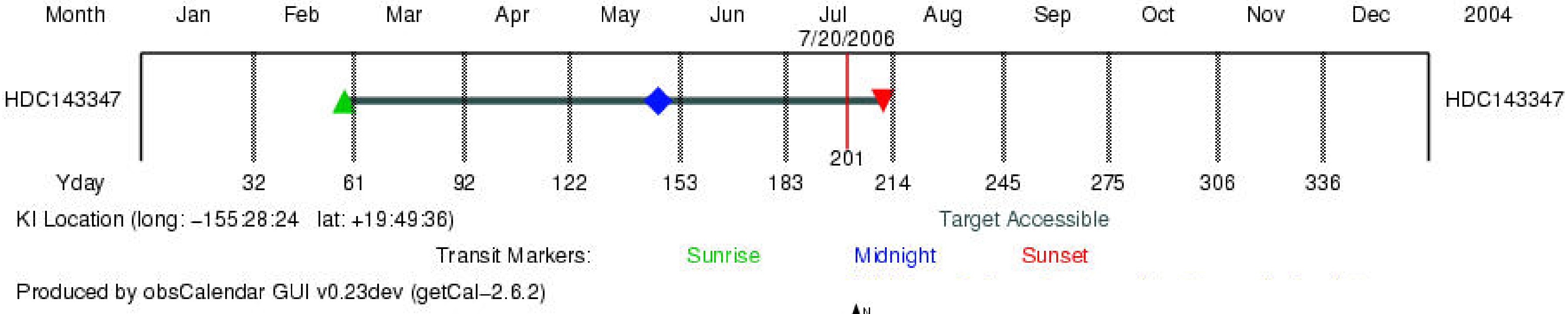
Next Steps?

- Did we answer our question?
  - Yes – rapid rotators can appear to be oblate (viewing angle)
  - See predicted von Zeipel gravity darkening
- Is there a way to improve this experiment?
  - More spectral resolution?
  - More sensitive instrument in order to get larger sample?

Example Number 3

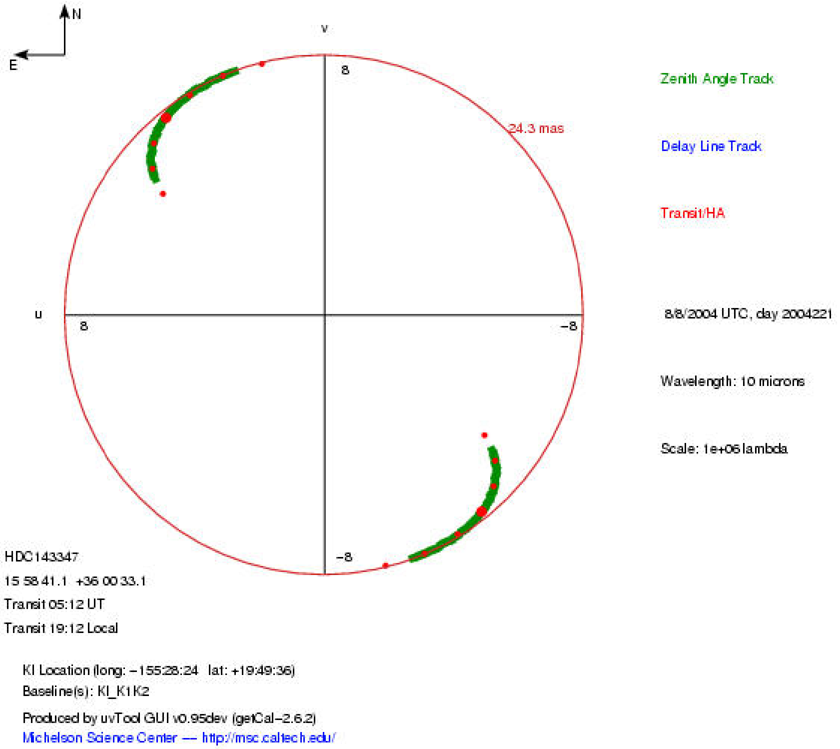
- Dust Species around mass-losing variable star – Mennesson et al. 2005, ApJ.
  - Hypothesis: Can we locate the dust formation location around a mass-losing star?
  - Instrumental choice: Dust is more readily observed at N band (and with spectral resolution we can learn something about the dust species) → Keck Interferometer KALI camera in non-nulling mode

When can I observe?



KI Location (long: −155:28:24 lat: +19:49:36)

Produced by obsCalendar GUI v0.23dev (getCal−2.6.2)



8/8/2004 UTC, day 2004221

Wavelength: 10 microns

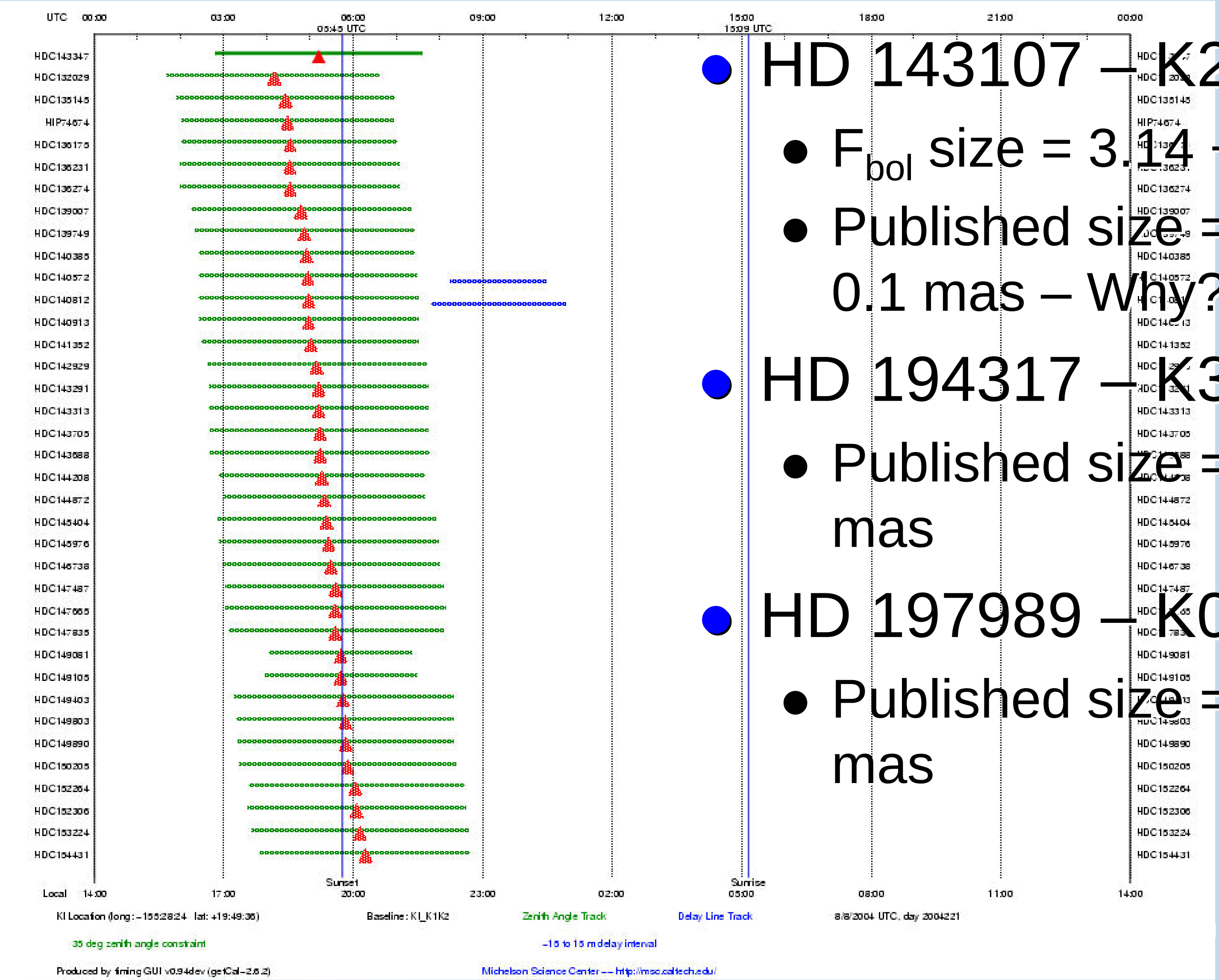
Scale: 1e+06 lambda

HDC143347
15 58 41.1 +36 00 33.1
Transit 05:12 UT
Transit 19:12 Local

KI Location (long: −155:28:24 lat: +19:49:36)
Baseline(s): KI_K1K2

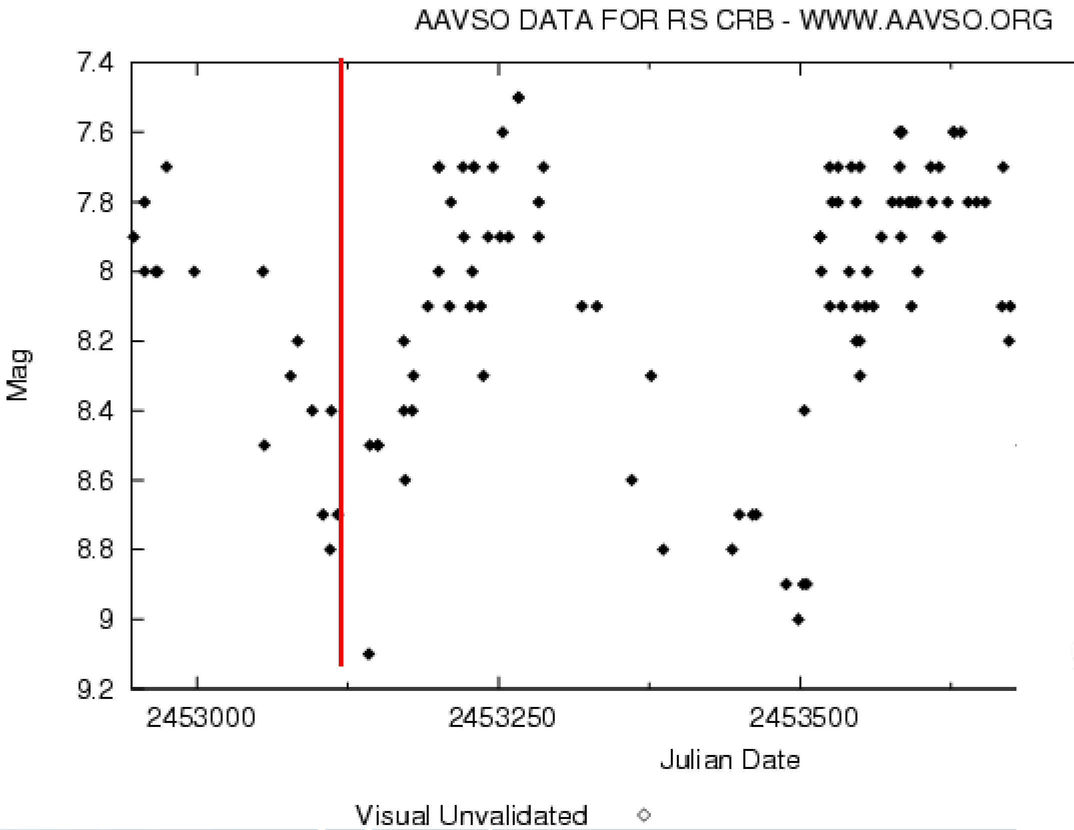
Produced by uvTool GUI v0.95dev (getCal−2.6.2)
Michelson Science Center — http://msc.caltech.edu/

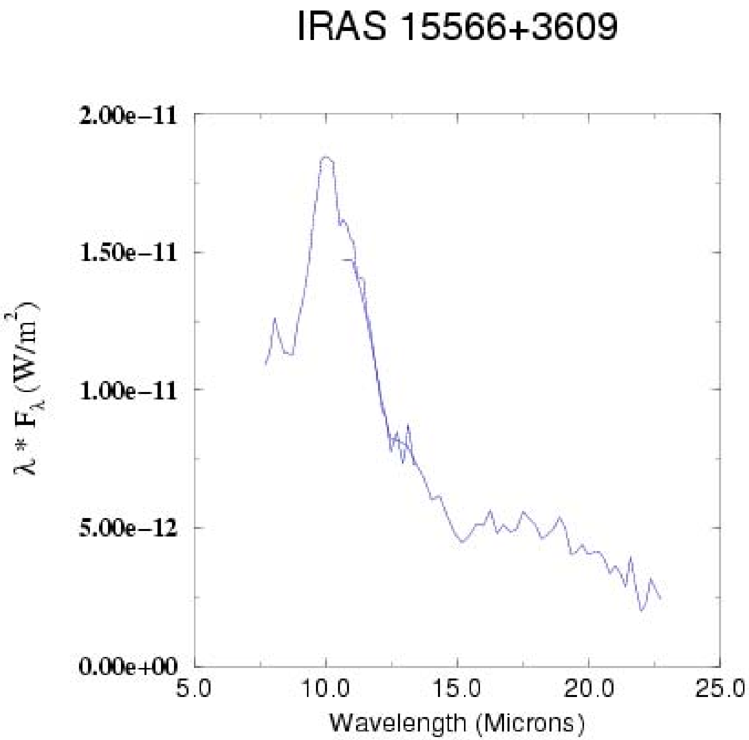
Calibration



- HD 143107 – K2III
  - F_{bol} size = 3.14 +/- 0.68 mas
  - Published size = 2.81 +/- 0.1 mas – Why?
- HD 194317 – K3III
  - Published size = 2.82 +/- 0.1 mas
- HD 197989 – K0III
  - Published size = 4.47 +/- 0.2 mas

Ancillary Data

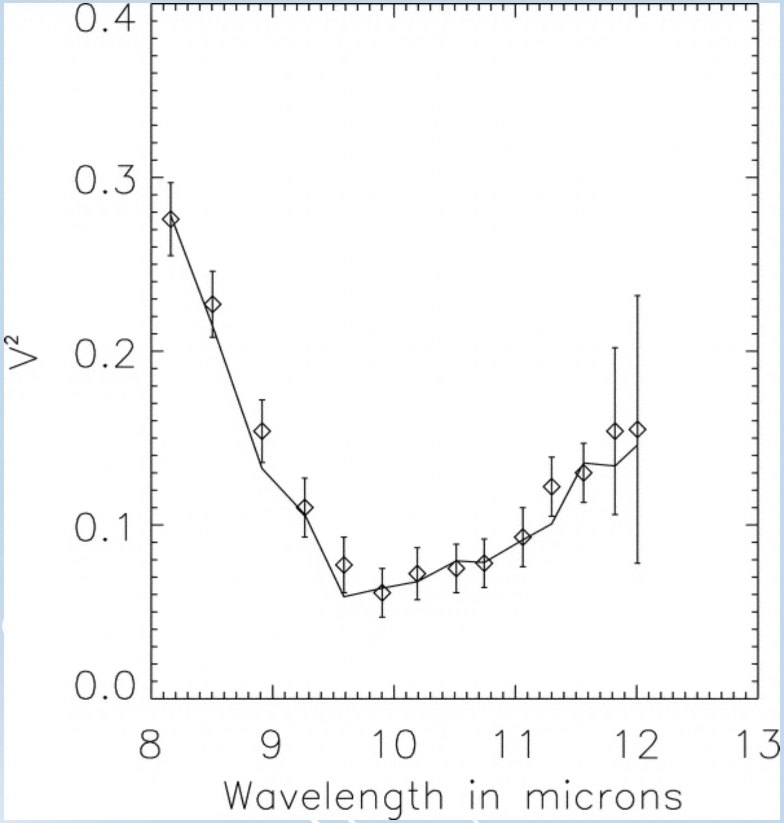


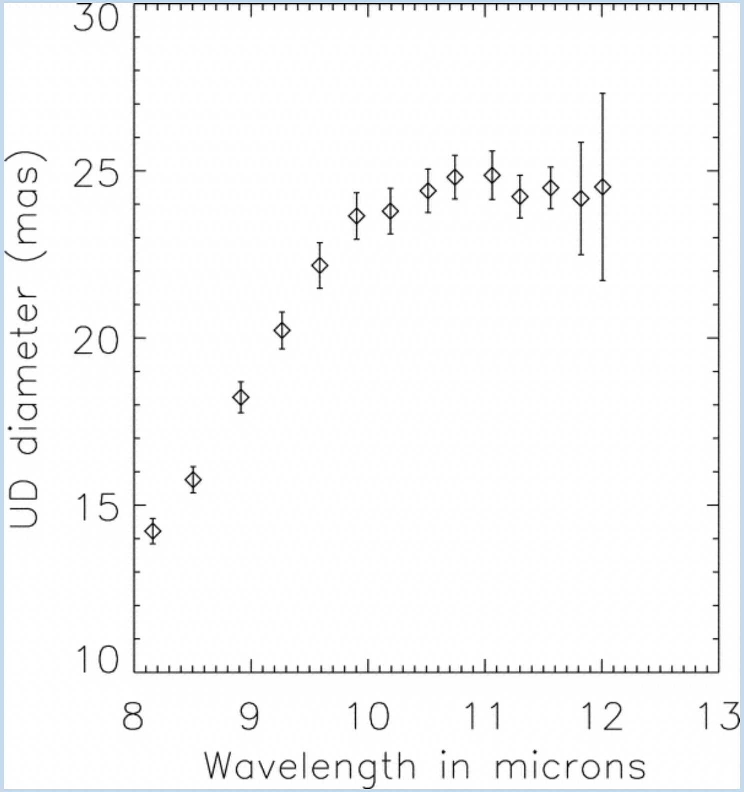


- Mid-infrared spectrum – IRAS LRS (right)
- AAVSO curve – phase (above)

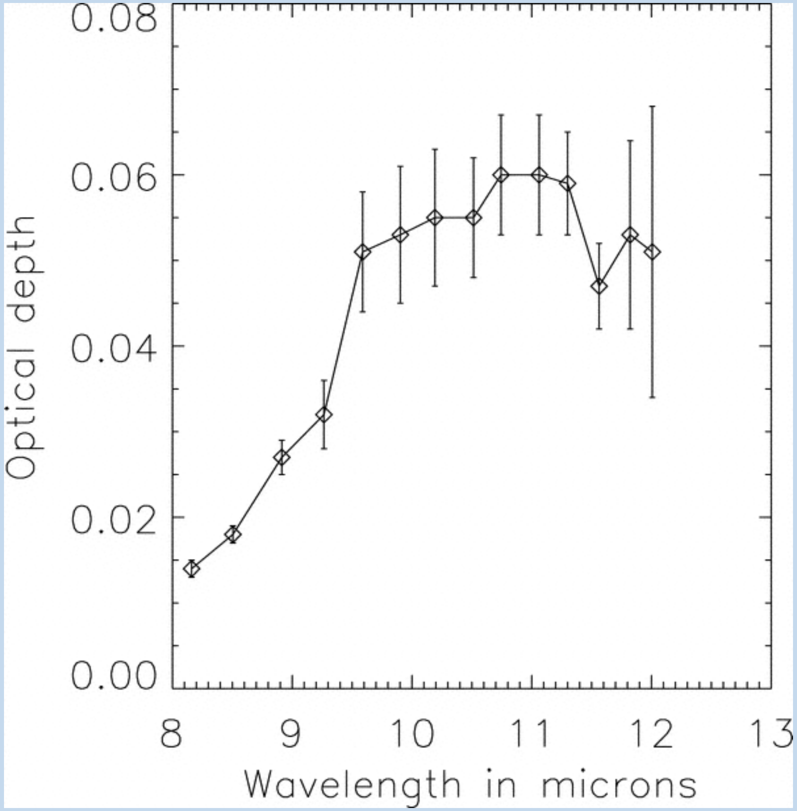
Results

- V^2 as function of wavelength (left)
- UD fits to spectral channels (below)





Published Results



Derived from spectrum from a single Keck and using best model parameters: star UD = 3.78 mas @ 3100K & shell UD = 27.6 mas @ 1160K – a Mg-rich silicate dust

Next Steps?

- Did we answer our question?
  - Yes – we detected the dust at a larger stellar radius than the photosphere and were able to understand a few things about the species.
- Is there a way to improve this experiment?
  - Plan ahead and have ancillary data that is contemporaneous – IR spectrum and light curve
  - Do with nulling “turned on”.

Final Steps in the Process…

- Reduce the data early and often
  - check quality, check tools, trace instrument behavior
- Model and perform fits
  - preliminary models, find out if need more info
- Include Error Estimates
  - systematics and observing uncertainties
- Don’t Hesitate to Ask for Assistance –
  - support scientists, colleagues, theorists,…
- PUBLISH!! – and then follow-up

Conclusions

- Good design of an observing program takes careful preparation. Think ahead.
- Data is only as good as its calibration.
- Try to be open to serendipity – there may be more in your data than you expect.
- Enjoy – you've got the best job in the world!