Ongoing Reduction of PTI Giant Diameters

"I'm Not Dead Yet"

Gerard van Belle
Lowell Observatory
March 19, 2013

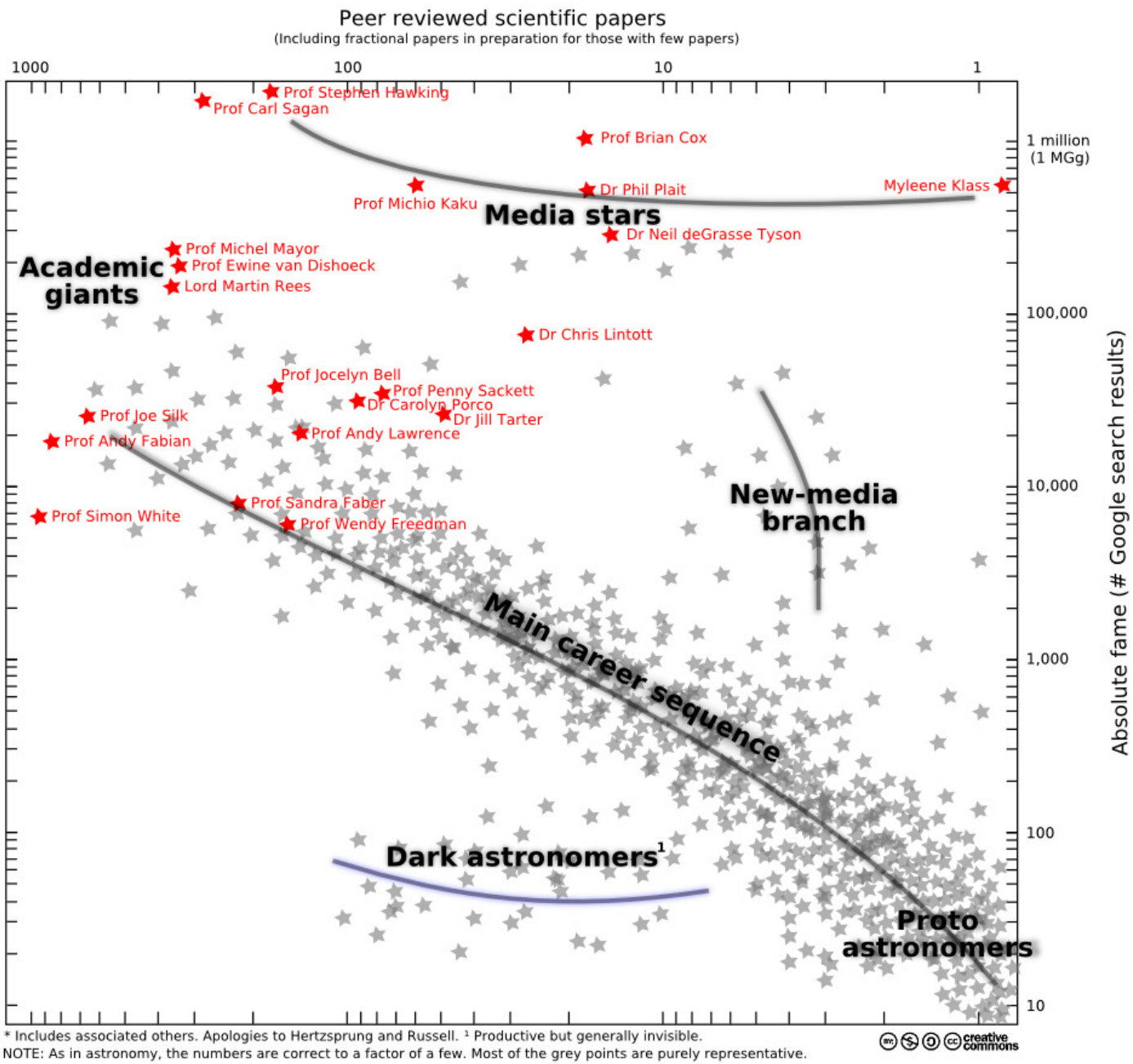
Palomar Testbed Interferometer

- 2-way beam combination
  - 3×50cm apertures
  - 110-m, 2×85m baselines
  - 3-way development incomplete
- H-, K-band operation
- Dual-beam astrometry demonstration
- Automated sequenced observations
  - Very good for survey work
- Operated 1996-2008
- *h*-index=30

A Tangential Note on *h*-index

- Number where a citation rank-ordered list of papers has the h^{th} paper number still greater than number of citations
- Attempts to quantify – in a single number – your productivity (number of papers) and your impact (number of citations)
  - Unintentionally ranks longevity, too
  - Eminently unfair, inaccurate, *and widely used*
  - It can be gamed
  - Applied to individuals and facilities
- One should be aware of one's *h*-index
  - And your Erdős–Bacon number, too (mine is 9)

The H-R diagram of Astronomers*



PTI's Greatest Hits

(ranked by citations for first paper of category)

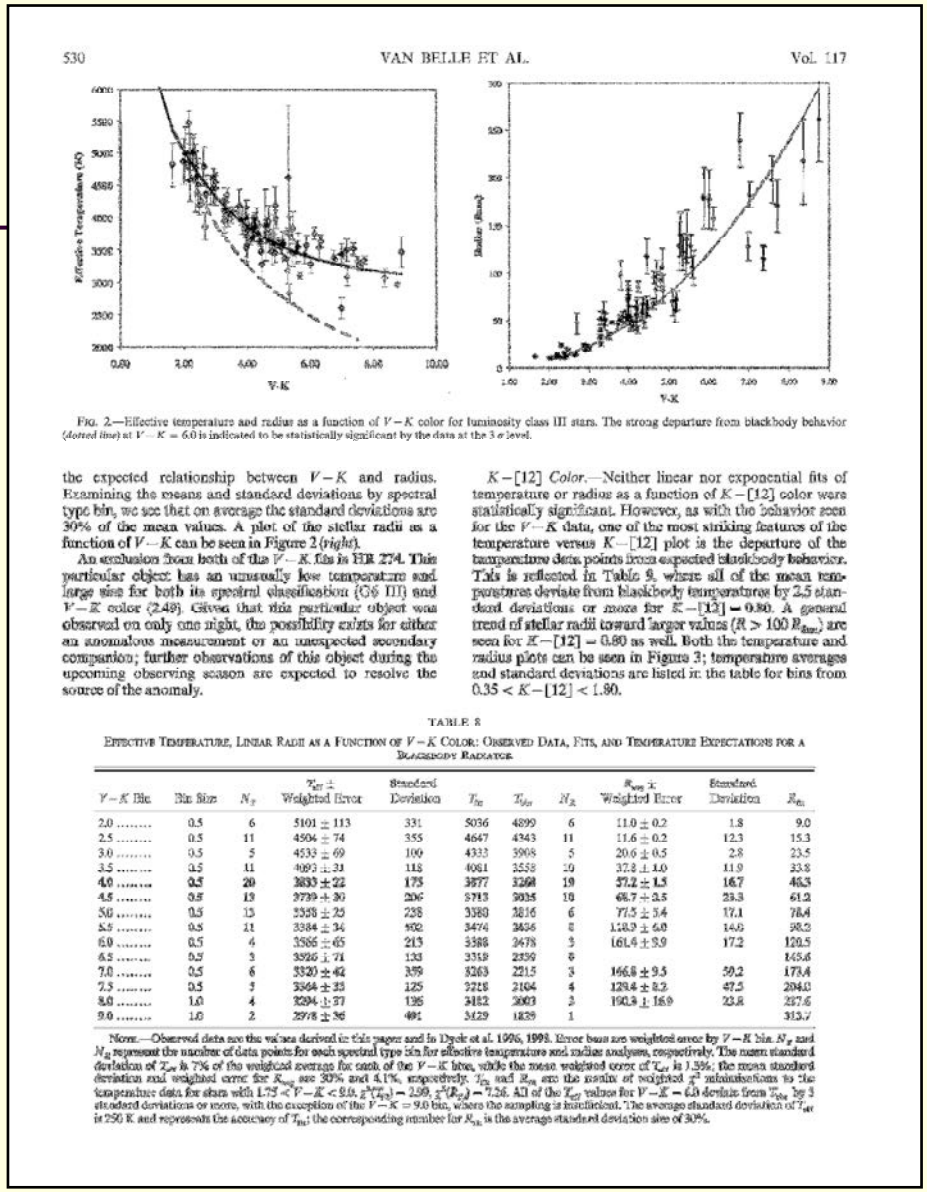
130

- Radii & T_{EFF} for GKM Giants (van Belle+ 1999)
- Herbig Ae/Be Stars (Eisner+ 2004, 2003, Kraus+ 2008, Eisner+ 2007)
- T Tauri stars (Eisner+ 2005, Akeson+ 2005, Akeson+ 2002, Akeson+ 2002)
- Altair oblateness (van Belle+ 2001, Domiciano de Souza+ 2005)
- Atlas distance (Pan+ 2004)
- M dwarf diameters (Lane+ 2001)
- FU Ori (Malbet+ 1998, Malbet+ 2005)
- Binary orbits: iota Peg, HD195987, 12 Boo, omi Leo, 64 Psc, HD9939 (Boden+ 1999, Torres+ 2002, Boden+ 2000, Hummel+ 2001, Boden+ 1999, 2006, 2005)
- Vega diameter (Ciardi+ 2001)
- Cepheids (Lane+ 2002, Lane+ 2000, Marengo+ 2003)
- PHASES (Lane & Muterspaugh 2004, Muterspaugh 2006, 2008, 2005, 2010)
- Miras (Thompson, Creech-Eakman & van Belle 2002a,b)
- Nova RS Oph, V838 Mon (Monnier+ 2006, Lane+ 2005)
- 51 Peg (Boden+ 1998)
- PTI Calibrators (van Belle+ 2008)

20

Giant Star Survey
(original)

- van Belle+ 1999: 59 giants
- Poor F_{BOL} data
  - SED fitting was crude
  - A_V correction was poor (at best)
- Old Hipparcos distances



530 VAN BELLE ET AL. Vol. 117

FIG. 2.—Effective temperature and radius as a function of $V-K$ color for luminosity class III stars. The strong departure from blackbody behavior (*dotted line*) at $V-K = 6.0$ is indicated to be statistically significant by the data at the 3 σ level.

the expected relationship between $V-K$ and radius. Examining the means and standard deviations by spectral type bin, we see that on average the standard deviations are 30% of the mean values. A plot of the stellar radii as a function of $V-K$ can be seen in Figure 2 (*right*).

An exclusion from both of the $V-K$ fits is HR 274. This particular object has an unusually low temperature and large size for both its spectral classification (G6 III) and $V-K$ color (2.49). Given that this particular object was observed on only one night, the possibility exists for either an anomalous measurement or an unexpected secondary companion; further observations of this object during the upcoming observing season are expected to resolve the source of the anomaly.

$K-[12]$ *Color.*—Neither linear nor exponential fits of temperature or radius as a function of $K-[12]$ color were statistically significant. However, as with the behavior seen for the $V-K$ data, one of the most striking features of the temperature versus $K-[12]$ plot is the departure of the temperature data points from expected blackbody behavior. This is reflected in Table 9, where all of the mean temperatures deviate from blackbody temperatures by 2.5 standard deviations or more for $K-[12] = 0.80$. A general trend of stellar radii toward larger values ($R > 100\ R_{bin}$) are seen for $K-[12] = 0.80$ as well. Both the temperature and radius plots can be seen in Figure 3; temperature averages and standard deviations are listed in the table for bins from $0.35 < K-[12] < 1.80$.

TABLE 8

EFFECTIVE TEMPERATURE, LINEAR RADII AS A FUNCTION OF $V-K$ COLOR: OBSERVED DATA, FITS, AND TEMPERATURE EXPECTATIONS FOR A BLACKBODY RADIATOR

$V-K$ Bin	Bin Size	N_T	T_{eff} ± Weighted Error	Standard Deviation	T_{fit}	T_{bb}	N_R	R_{avg} ± Weighted Error	Standard Deviation	R_{fit}
2.0	0.5	6	5101 ± 113	331	5036	4899	6	11.0 ± 0.2	1.8	9.0
2.5	0.5	11	4504 ± 74	355	4647	4343	11	11.6 ± 0.2	12.3	15.3
3.0	0.5	5	4533 ± 69	109	4333	3908	5	20.6 ± 0.5	2.8	23.5
3.5	0.5	11	4093 ± 33	118	4061	3558	10	37.8 ± 1.0	11.9	33.8
4.0	0.5	20	3833 ± 22	175	3877	3268	19	57.2 ± 1.5	16.7	46.5
4.5	0.5	19	3739 ± 30	206	3743	3035	18	68.7 ± 2.5	23.3	61.2
5.0	0.5	15	3558 ± 29	238	3580	3816	6	77.5 ± 5.4	17.1	78.4
5.5	0.5	11	3384 ± 34	402	3474	3636	8	118.3 ± 6.0	14.6	98.2
6.0	0.5	4	3565 ± 65	213	3388	3478	3	161.4 ± 9.9	17.2	120.5
6.5	0.5	3	3926 ± 71	133	3318	2339	6			145.6
7.0	0.5	6	3320 ± 42	359	3263	2215	3	166.8 ± 9.5	59.2	173.4
7.5	0.5	5	3364 ± 33	125	3218	2104	4	129.4 ± 8.2	47.5	204.0
8.0	1.0	4	3294 ± 37	136	3182	2009	3	190.3 ± 16.9	23.8	237.6
9.0	1.0	2	2978 ± 36	491	3029	1839	1			315.7

NOTE.—Observed data are the values derived in this paper and in Dyck et al. 1996, 1998. Error bars are weighted error by $V-K$ bin. N_T and N_R represent the number of data points for each spectral type bin for effective temperature and radius analyses, respectively. The mean standard deviation of T_{eff} is 7% of the weighted average for each of the $V-K$ bins, while the mean weighted error of T_{eff} is 1.5%; the mean standard deviation and weighted error for R_{avg} are 30% and 4.1%, respectively. T_{fit} and R_{fit} are the results of weighted χ^2 minimizations to the temperature data for stars with $1.75 < V-K < 9.0$, $\chi^2(T_{fit}) = 2.99$, $\chi^2(R_{fit}) = 7.26$. All of the T_{eff} values for $V-K = 6.0$ deviate from T_{bb} by 3 standard deviations or more, with the exception of the $V-K = 9.0$ bin, where the sampling is insufficient. The average standard deviation of T_{eff} is 250 K and represents the accuracy of T_{fit}; the corresponding number for R_{fit} is the average standard deviation size of 30%.

Giant Star Survey MkII

- Significantly larger sample
  - 240 ‘normal’ giants
    - 9.6 nights each
  - 63 Miras
    - 17 nights each
    - Some up to 97 nights
- Improved SED fitting (see next)
- New Hipparcos distances: 2-3× improvement

GIANTS

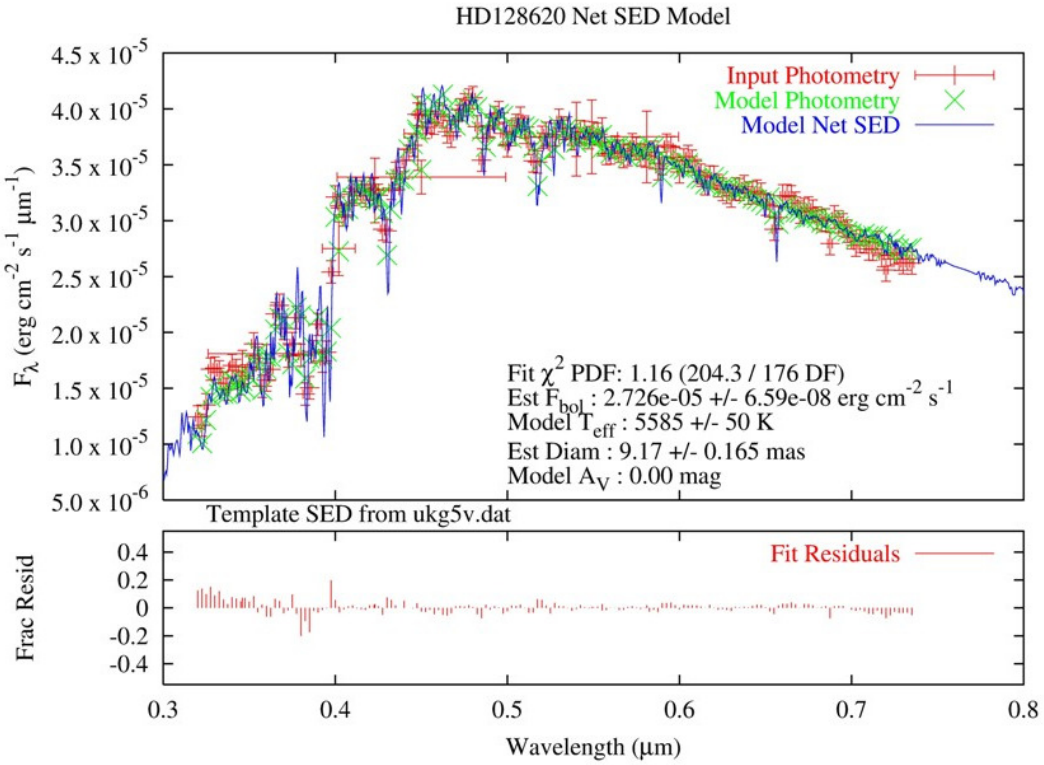
SpType	Nstars	Avgnights
G0	1	4.0
G2	1	14.0
G5	3	22.7
G6	1	10.0
G7	6	17.2
G8	27	8.7
G9	9	14.7
K0	17	14.5
K1	12	14.7
K2	22	5.7
K3	19	9.4
K4	19	15.0
K5	30	11.2
K7	2	4.5
M0	9	5.0
M1	11	3.5
M2	13	4.3
M3	13	5.7
M4	8	5.9
M5	4	4.0
M6	6	19.7
M7	1	4.0
M8	5	6.8
M9	1	6.0

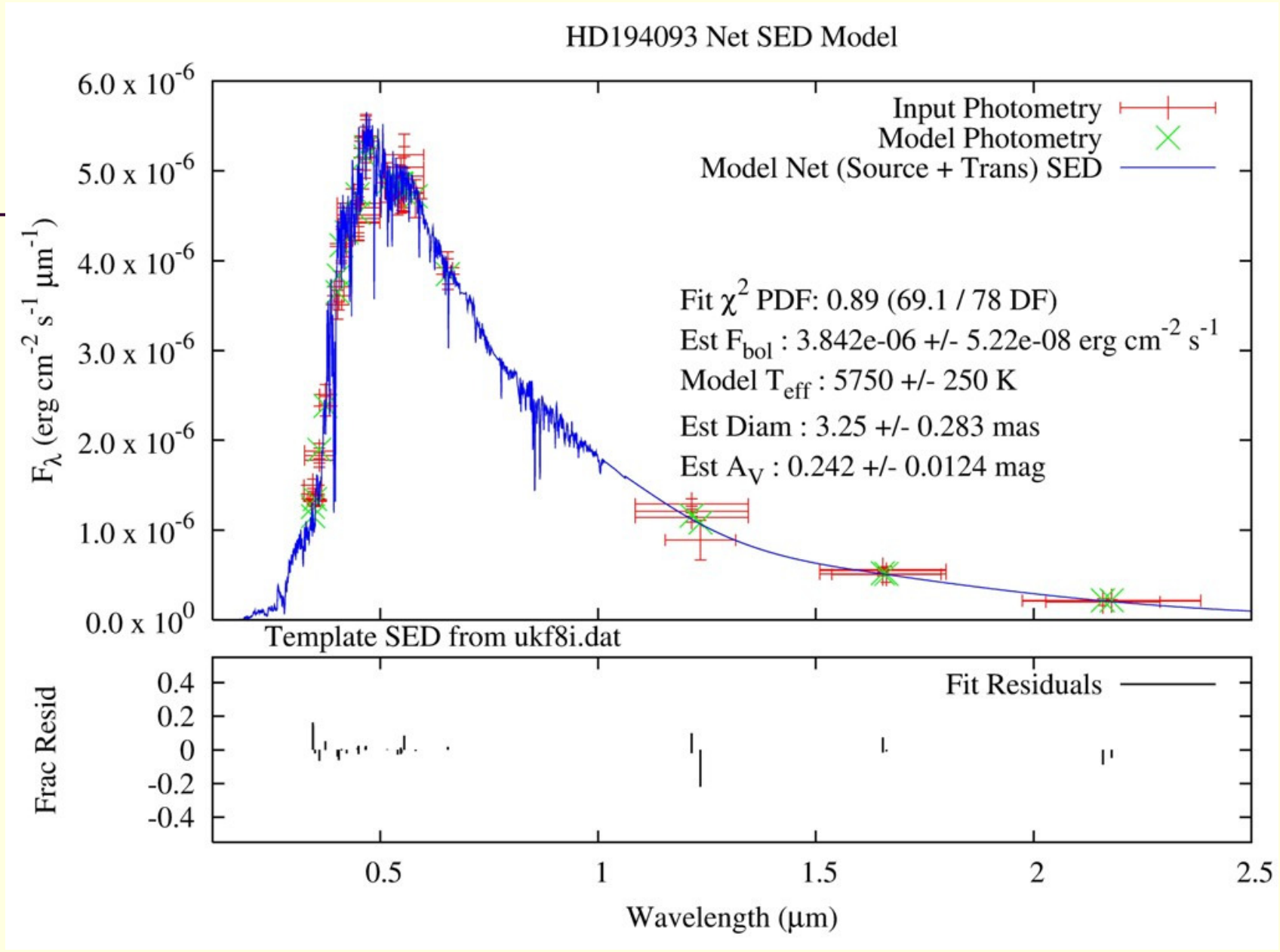
MIRAS

SpType	Nstars	Avgnights
M2	1	4.0
M3	6	29.3
M4	14	23.9
M5	18	24.2
M6	13	11.6
M7	4	9.8
M8	3	26.7
M9	3	7.7

Improved SED Fitting

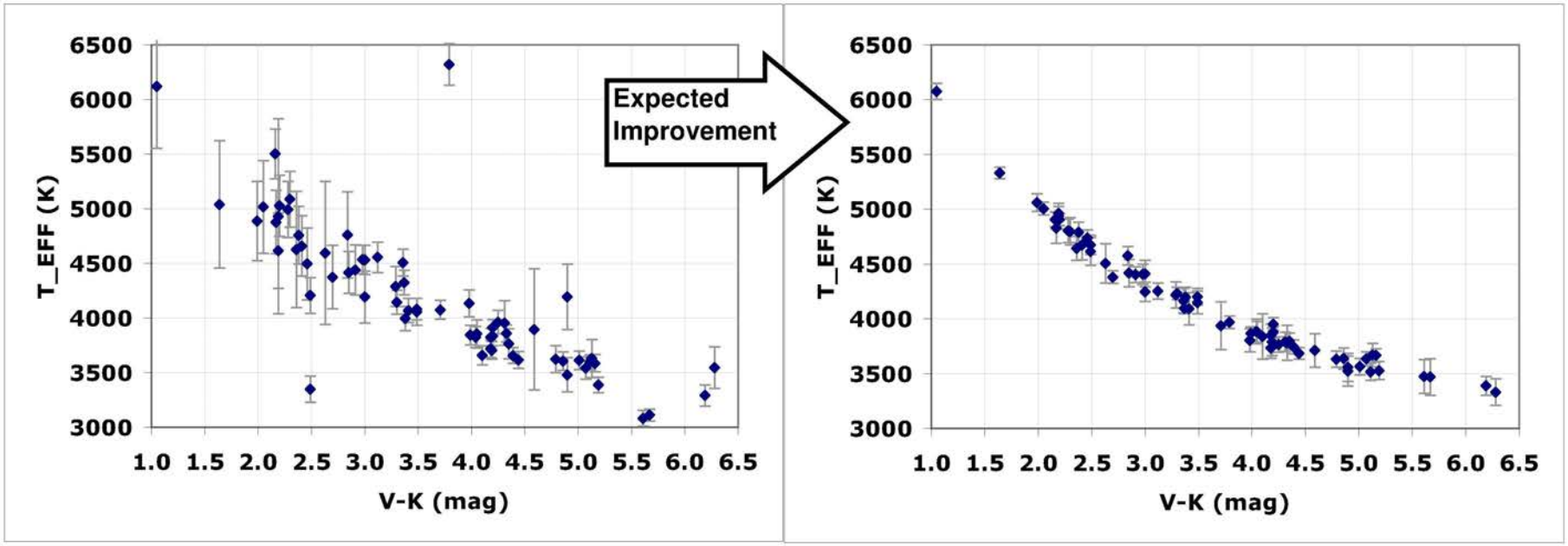
- Far richer photometry data sets
  - VizieR, GCPD
- Empirical spectral templates
  - Pickles (1998)
- True reddening fitting
- Spectrophotometry now also available
- F_{BOL} errors improve from ~10% to ~0.5%
  - Had been limiting term in T_{EFF} determinations
- New AndyCode™ - sedFit v2.0 in 'alpha' testing




HD194093 Net SED Model
Input Photometry
Model Photometry
Model Net (Source + Trans) SED
Fit χ2 PDF: 0.89 (69.1 / 78 DF)
Est Fbol : 3.842e-06 +/- 5.22e-08 erg cm-2 s-1
Model Teff : 5750 +/- 250 K
Est Diam : 3.25 +/- 0.283 mas
Est AV : 0.242 +/- 0.0124 mag
Fλ (erg cm-2 s-1 μm-1)
6.0 x 10-6
5.0 x 10-6
4.0 x 10-6
3.0 x 10-6
2.0 x 10-6
1.0 x 10-6
0.0 x 100
Template SED from ukf8i.dat
Fit Residuals
Frac Resid
0.4
0.2
0
-0.2
-0.4
0.5
1
1.5
2
2.5
Wavelength (μm)

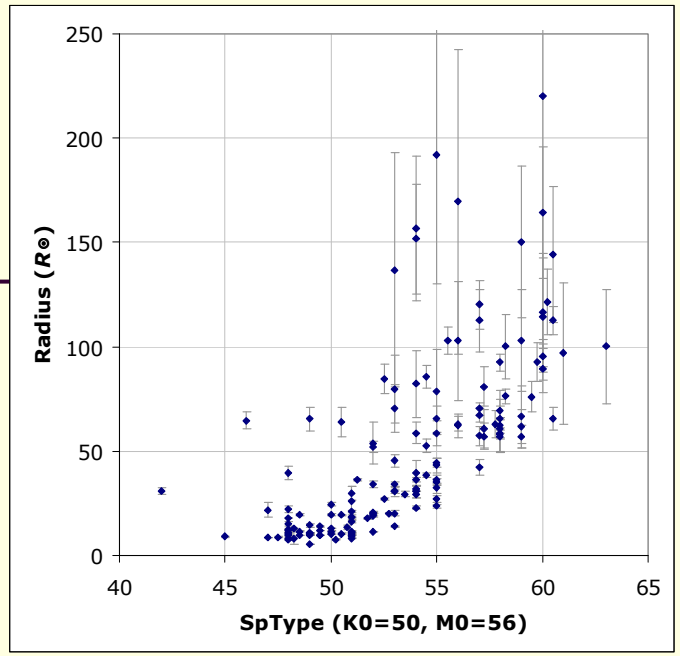
Expected Improvement: T_{EFF}

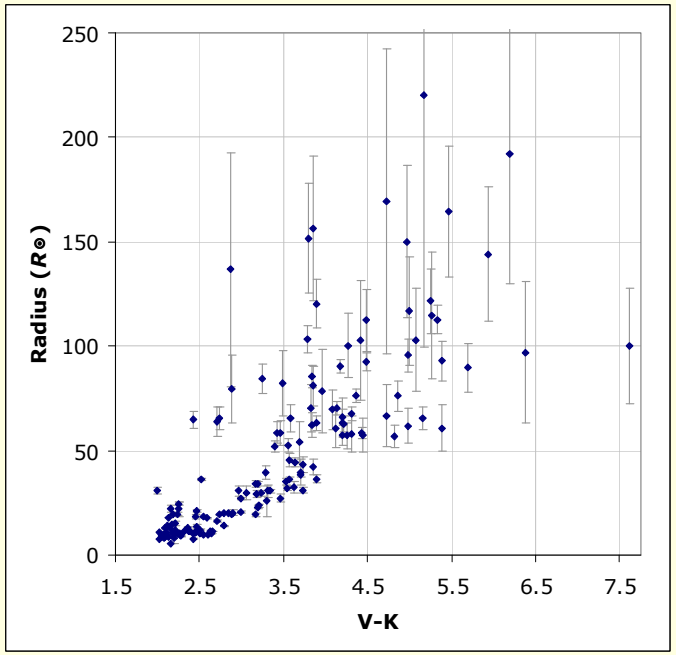
- σ_{TEFF}~125K should improve to σ_{TEFF}~25K
- Entirely new realm of precision
  - Can explore 2nd order effects – eg. metallicity



Preliminary Radius Results

- As a function of spectral type and V-K color
- Still need de-redden V-K results
- Separation of (mis-) classification of luminosity types?
- Highlights the need for better parallaxes
  - Some benefit from Gaia, but bright limit will be a problem





NPOI Data

- Matching V-band data for this sample
  - Currently ~30 objects with NPOI & PTI data
- Insights on limb darkening
  - eg. Predicted by Davis Tango & Booth (2000), but needs to be measured

PTI Data Flow

- Level 0 – raw data
- Level 1 – instrument calibrated
  - eg. flat, dark, ratio corrected, ‘data editing’

  ← end of night script
- Level 2 – observationally calibrated
  - normalized V^2’s

  ← `wbCalib` / `nbCalib`
- Level 3 – model applied
  - eg. uniform disk fit

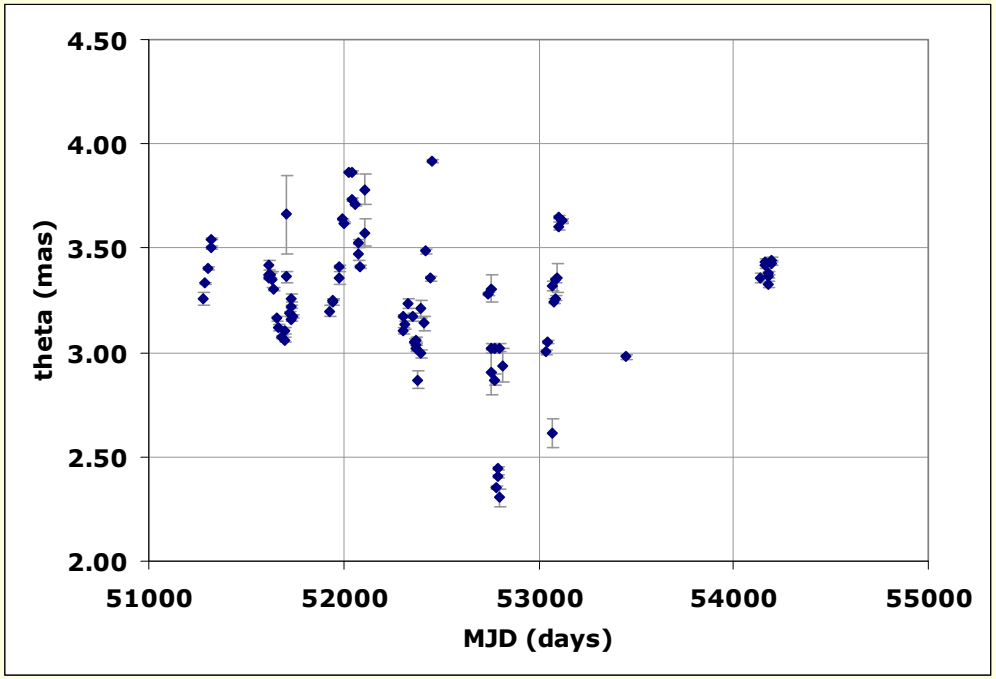
  ← `fitSingle`

    ← wrapper scripts

[Data Flow Demonstration Here]

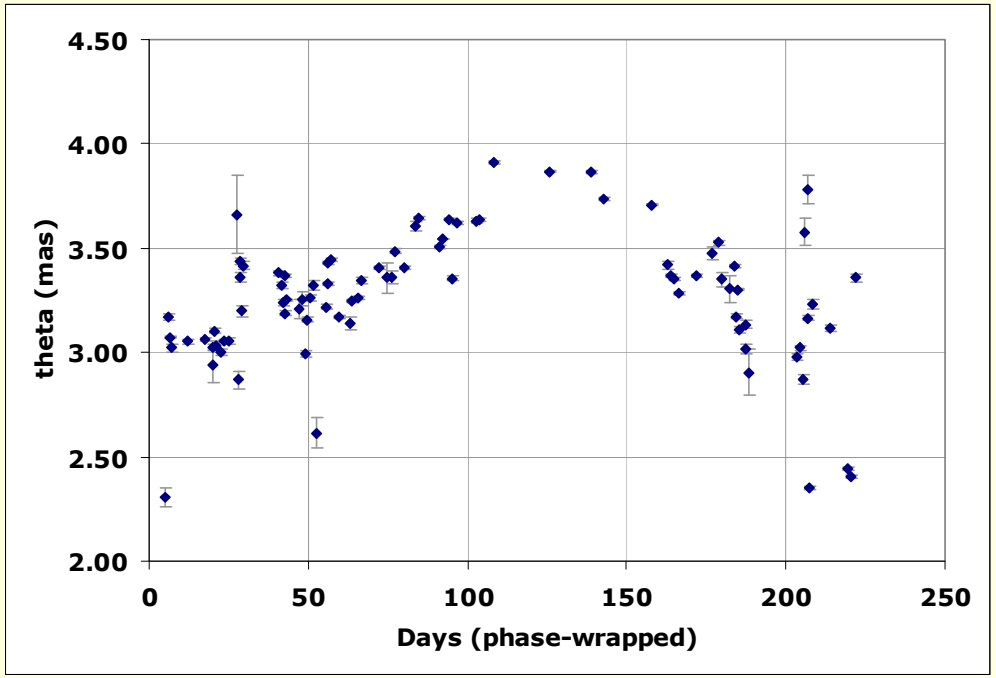
Example Mira Variable: R Boo

- Period = 223d
- SpType = M4e-M8e
- Observed 88 nights over 8 years (!)
- Follows up on findings of Thompson+ (2002a,b) and van Belle+ (1996, 1997, 2002)



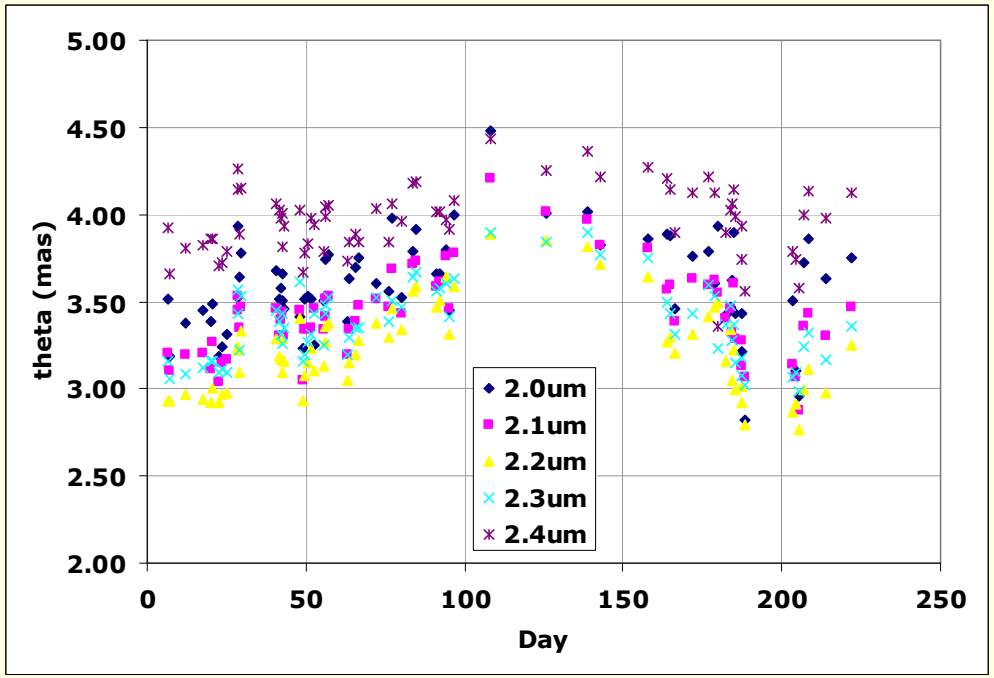
Example Mira Variable: R Boo

- Period = 223d
- SpType = M4e-M8e
- Observed 88 nights over 8 years (!)
- Follows up on findings of Thompson+ (2002a,b) and van Belle+ (1996, 1997, 2002)



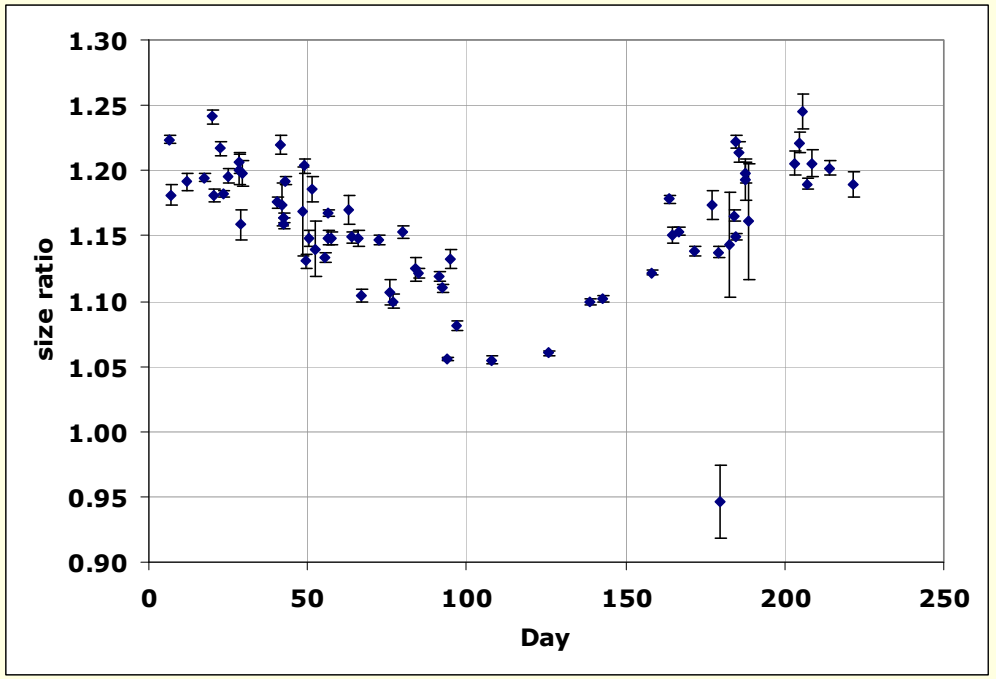
Example Mira Variable: R Boo

- Period = 223d
- SpType = M4e-M8e
- Observed 88 nights over 8 years (!)
- Follows up on findings of Thompson+ (2002a,b) and van Belle+ (1996, 1997, 2002)



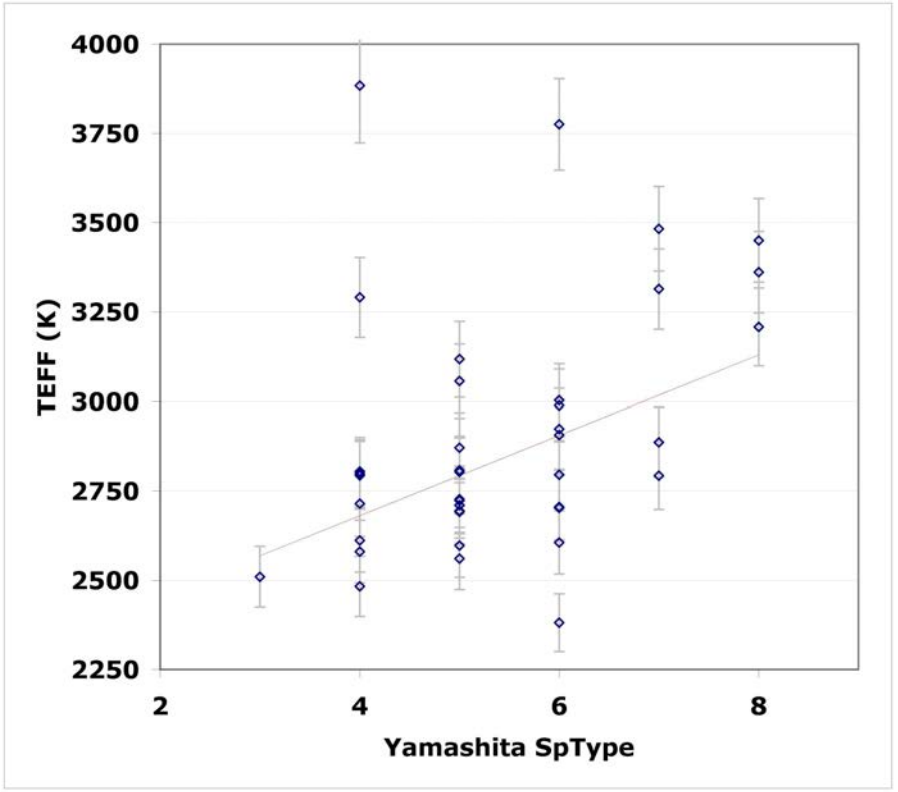
Example Mira Variable: R Boo

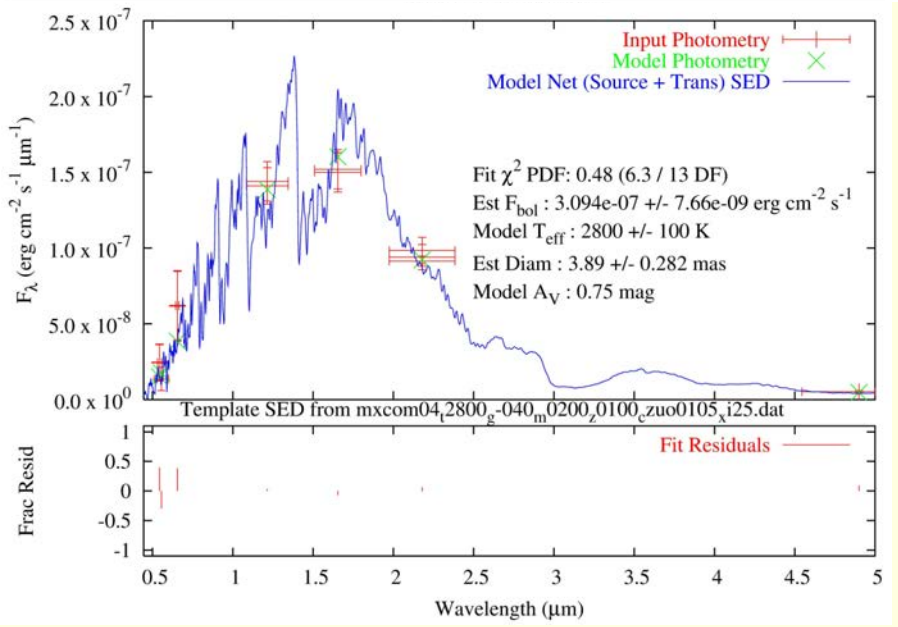
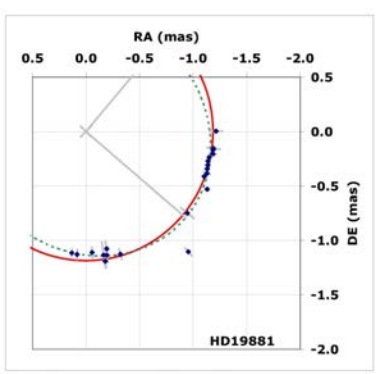
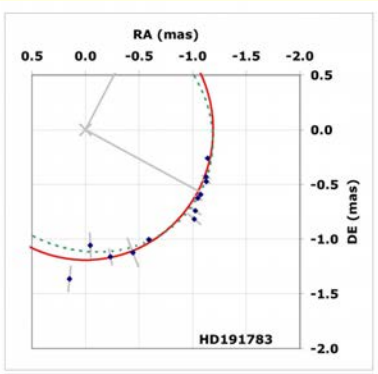
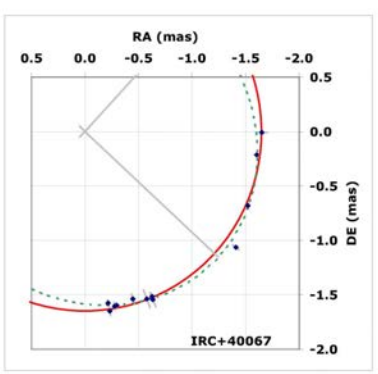
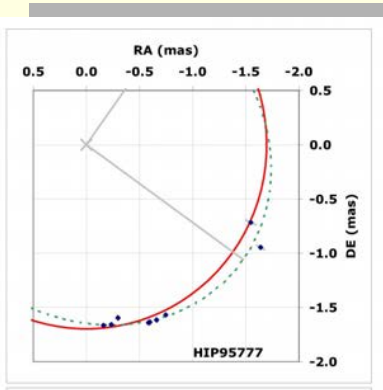
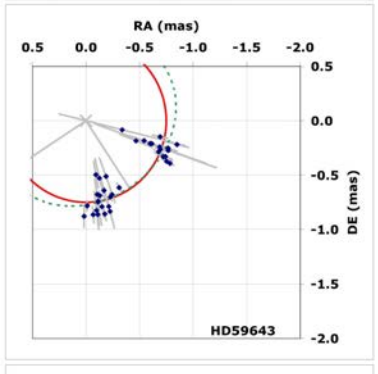
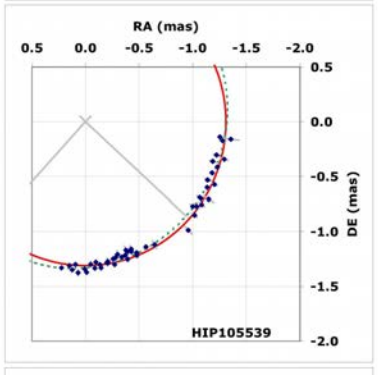
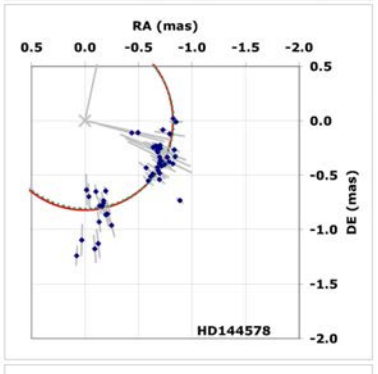
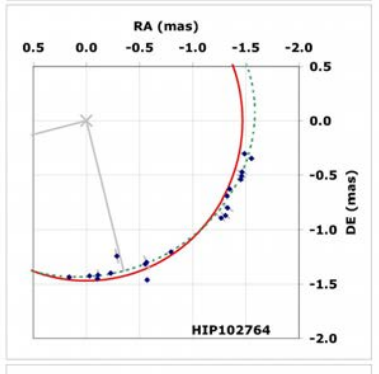
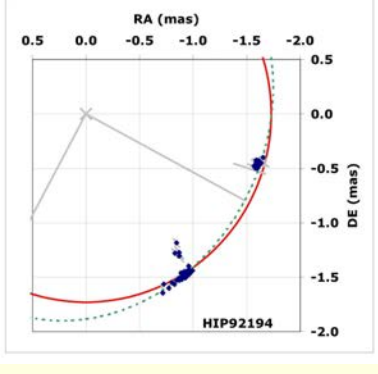
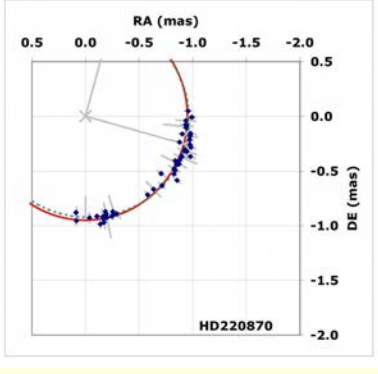
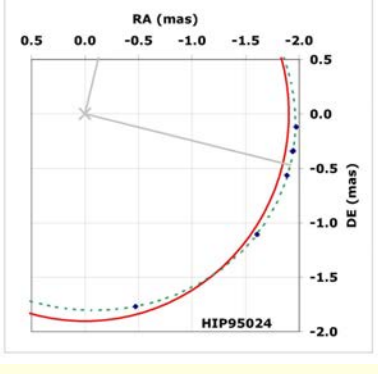
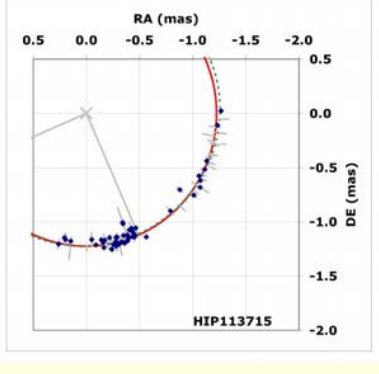
- Period = 223d
- SpType = M4e-M8e
- Observed 88 nights over 8 years (!)
- Follows up on findings of Thompson+ (2002a,b) and van Belle+ (1996, 1997, 2002)



PTI Carbon Stars

- 41 stars with diameters
  - T_{EFF} determination
  - *R* difficult, distances poor
- Roughly a dozen with multiple baselines
  - Sufficient {u,v} for 'shapes'
- Are all carbon stars 'non-spherical'?
  - Hot spots
  - Rotationally oblate





PTI Carbon Stars