

Finding Calibrator Stars

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Outline

Visibility Calibration & Role of Calibration Stars

What Makes a Good Calibration Star?

Stellar Angular Sizes

Stellar Multiplicities

Choosing Calibrators

Observing Targets and Calibrators: Practical Considerations

Summary

Visibility Calibration & Role of Calibrator Stars

An Interferometer is a Device that *Measures* the *Interference* (or *Coherence*) of a Wave-like Phenomena (e.g. Incident Starlight – C.Haniff)

In Astronomical Interferometry We Use the Degree or Amount of Interference (the *Visibility*) as Proxy for Source Morphological Properties

“Unresolved” Sources have High Visibility

“Resolved” Sources have Low(er) Visibility (**This is Where the Science is...**)

But Our Interferometer is **Imperfect** at Measuring Coherence – So How Do We Gauge the **Degree of Imperfection**?

Duh! – Measure the Coherence of Sources With “Known” (i.e. Model-able) Coherence Properties and “Compare”...

Visibility Calibration & Role of Calibrator Stars (2)

Interferometer Measures Coherence of Target

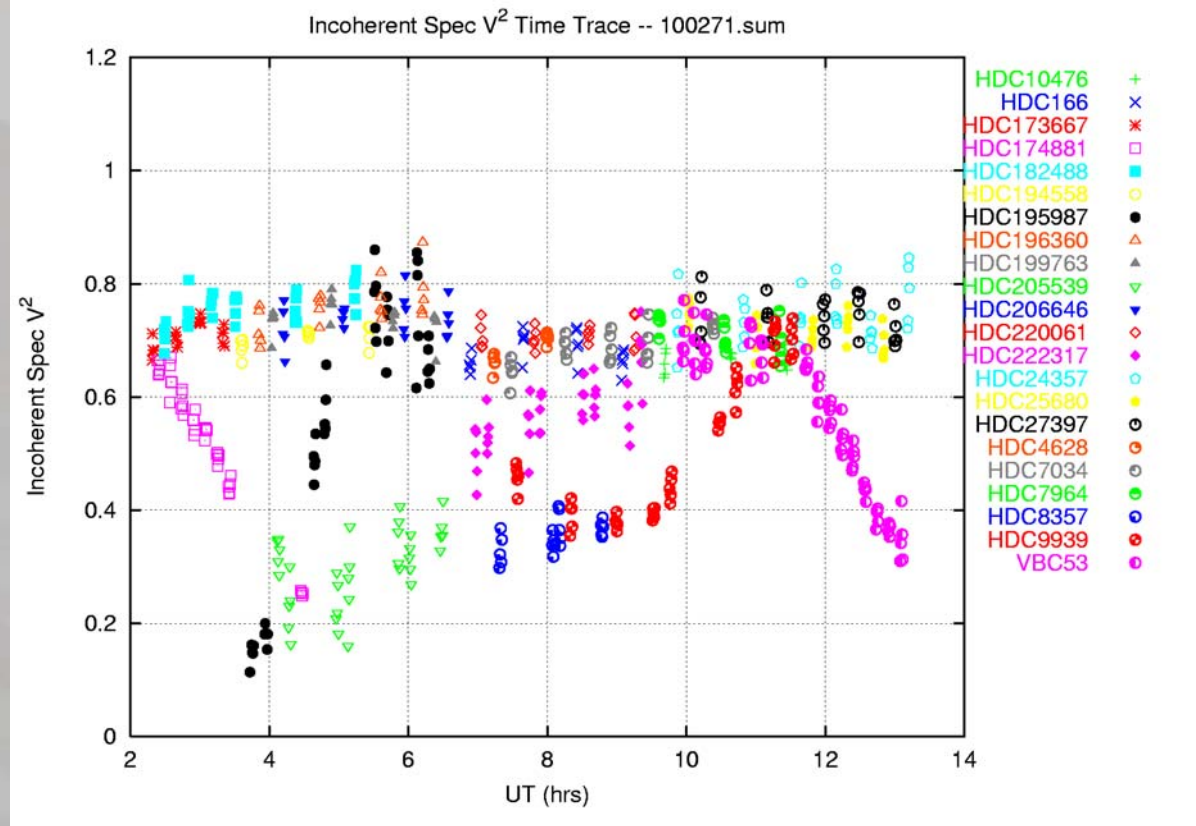
=> Calibrator Measures In-Coherence of Interferometer

V^2 Data
From PTI

Calibration
Multiplicatively
Applied

$$V^2_{Target} = V^2_{Meas} / V^2_{Sys}$$

$$V^2_{Sys} = V^2_{Calib} / V^2_{Calib-Model}$$



What Makes a Good Calibration Source?

Attributes of a Good Calibrator:

- Bright – Lots of Signal

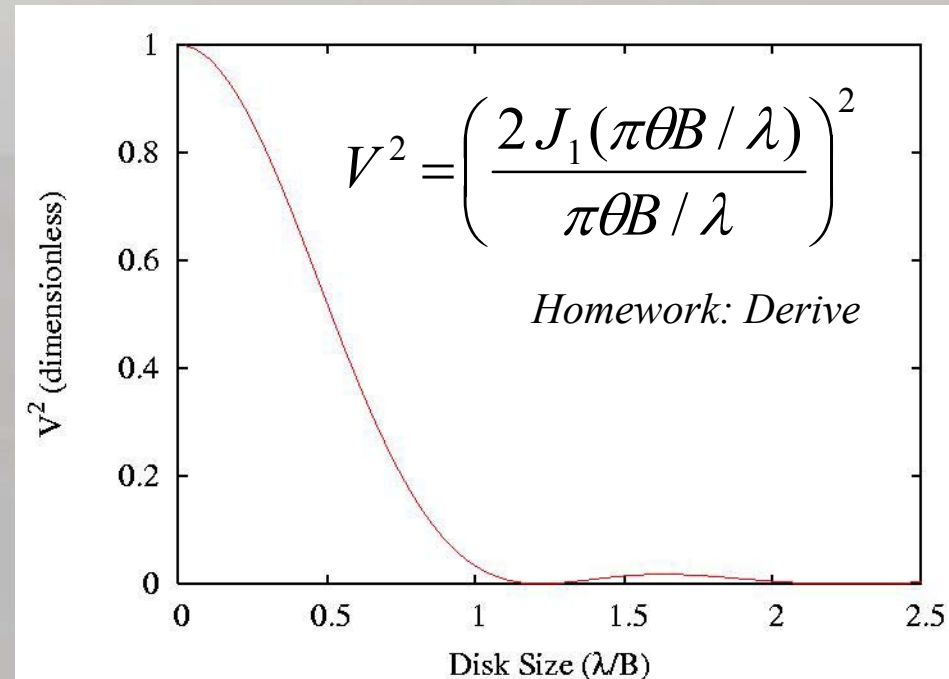
$$SNR \propto NV^2$$

- Point-like (Unresolved) – Little Modeling Error

$$\sigma_{V^2 - Sys} \propto \frac{\partial V^2}{\partial \theta} \sigma_{\theta}$$

- These Two Properties are **Fundamentally At Odds** With Each Other

Uniform Disk Visibility Model



Stellar Angular Sizes

$$A = \oint dA = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta r^2 \sin \theta = 4\pi r^2$$

So How Big Do Stars Appear Anyway?

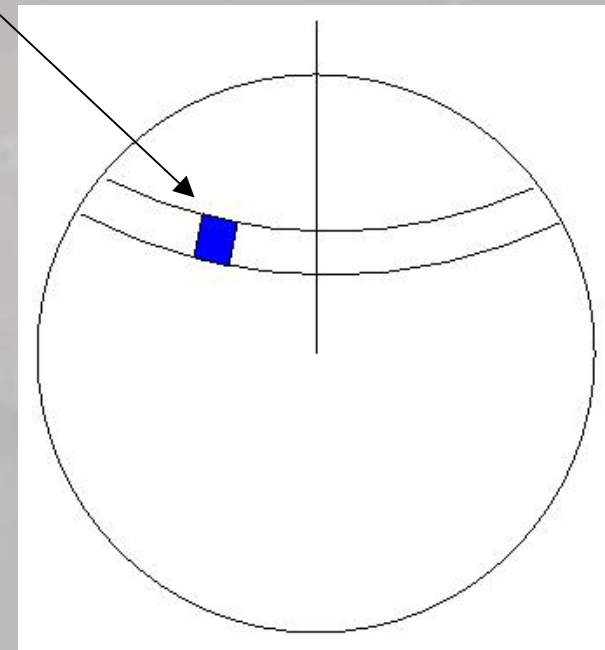
One Solution is to “Know” the Linear Size and Distance

$$\theta_{sun} = d_{sun} / D \\ \cong [0.01 AU] / [10 pc] = 10^{-3} \text{ arc sec} \cong 1 \text{ mas}$$

Imagine that Stars are Spheres Whose Photosphere's are at an “Effective” Temperature T

Imagine the Star's Photosphere is a Lambertian Blackbody Radiator..

$$dA = r^2 \sin \theta d\theta d\phi$$



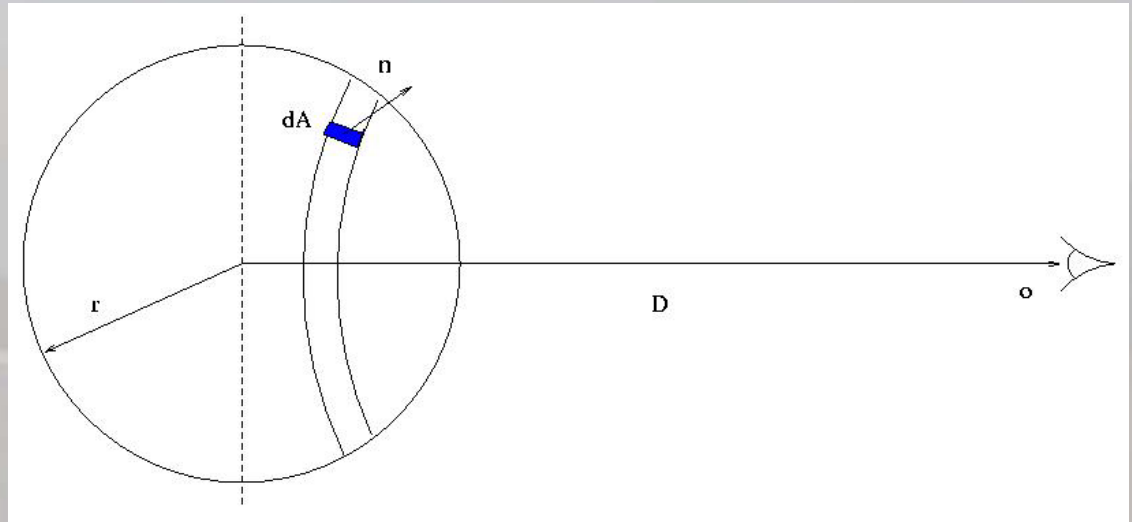
Angular Sizes of Stars (2)

Radiation per unit star surface area into unit solid angle:

$$\sigma T_{eff}^4 \frac{\hat{n} \cdot \hat{o}}{\pi} = \frac{\sigma T_{eff}^4}{\pi} \cos \theta$$

Radiation per unit star surface area per unit area at D:

$$\frac{\sigma T_{eff}^4}{\pi} \cos \theta / D^2$$



Homework: Derive For Yourself

Integrated (Bolometric) Flux at

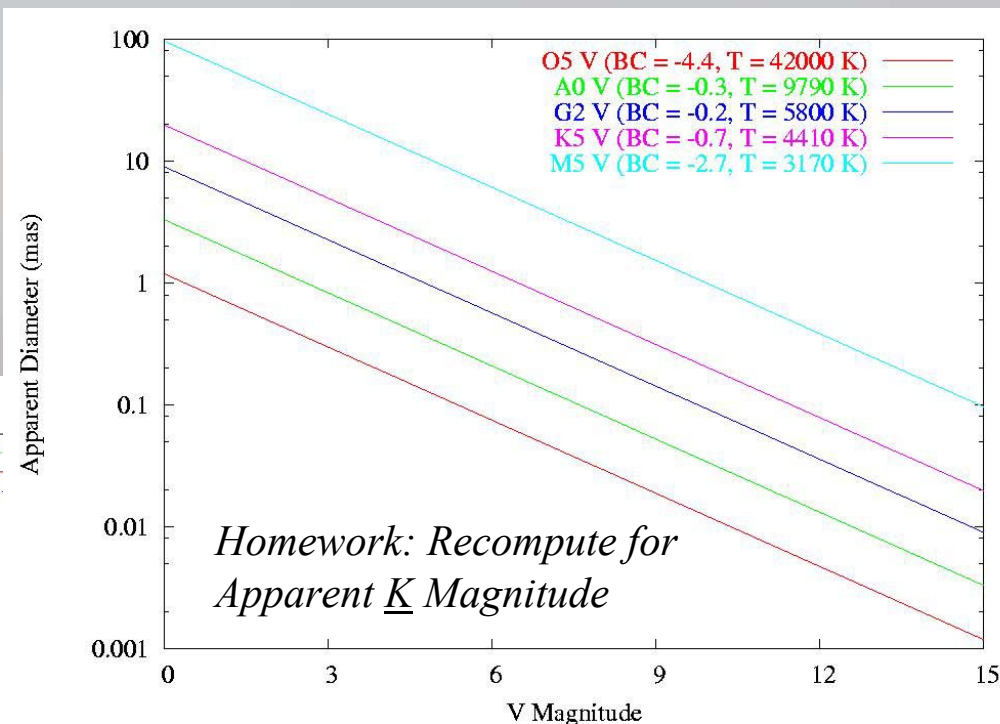
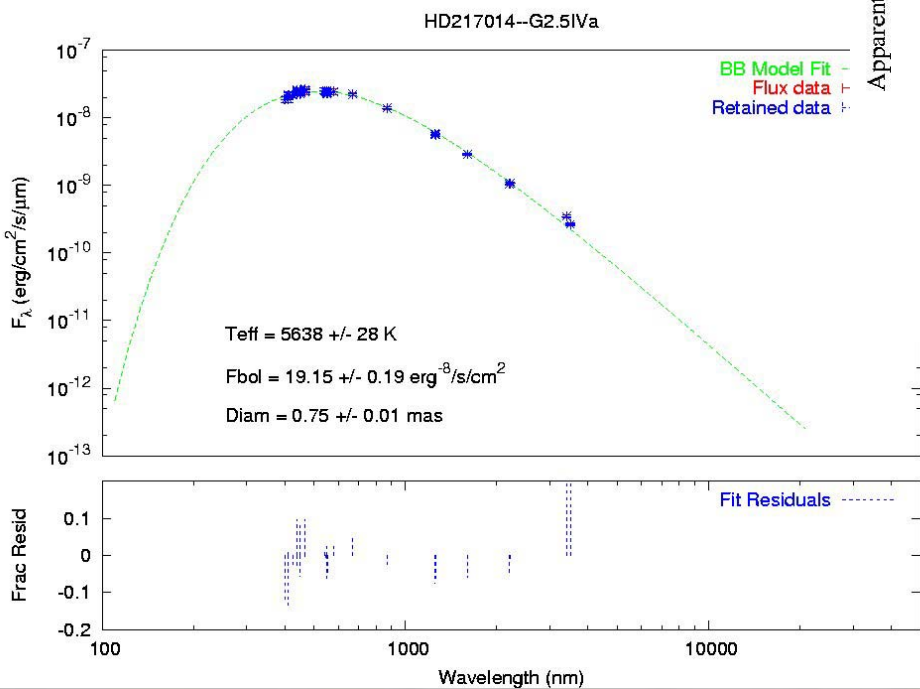
$$\text{Distance } D: F_{Bol} = \int_{2\pi} dA \frac{\sigma T_{eff}^4}{\pi} \cos \theta / D^2 = \frac{r^2}{\pi D^2} \sigma T_{eff}^4 \int_{2\pi} d\theta d\phi \sin \theta \cos \theta$$

$$= \frac{1}{2} \frac{4r^2}{D^2} \sigma T_{eff}^4 \left[\frac{1}{2} \sin^2 \theta \right]_0^{\pi/2} = \frac{1}{4} \Theta^2 \sigma T_{eff}^4$$

Angular Sizes of Stars (3)

$$\Theta = \sqrt{\frac{4 F_{Bol}}{\sigma T_{eff}^4}}$$

$$= 8.17 \text{ mas} \cdot 10^{-0.2(V+BC)} \cdot \left[\frac{T_{eff}}{5800 \text{ K}} \right]^{-2}$$



- Because Stellar Size is Proportional to (sqrt of) Brightness, Bright & “Point-like” Does Not Formally Exist
- Question of Interferometer Resolution and Sensitivity
- For Fixed Magnitude, Hotter Stars Are Smaller

Stellar Multiplicity

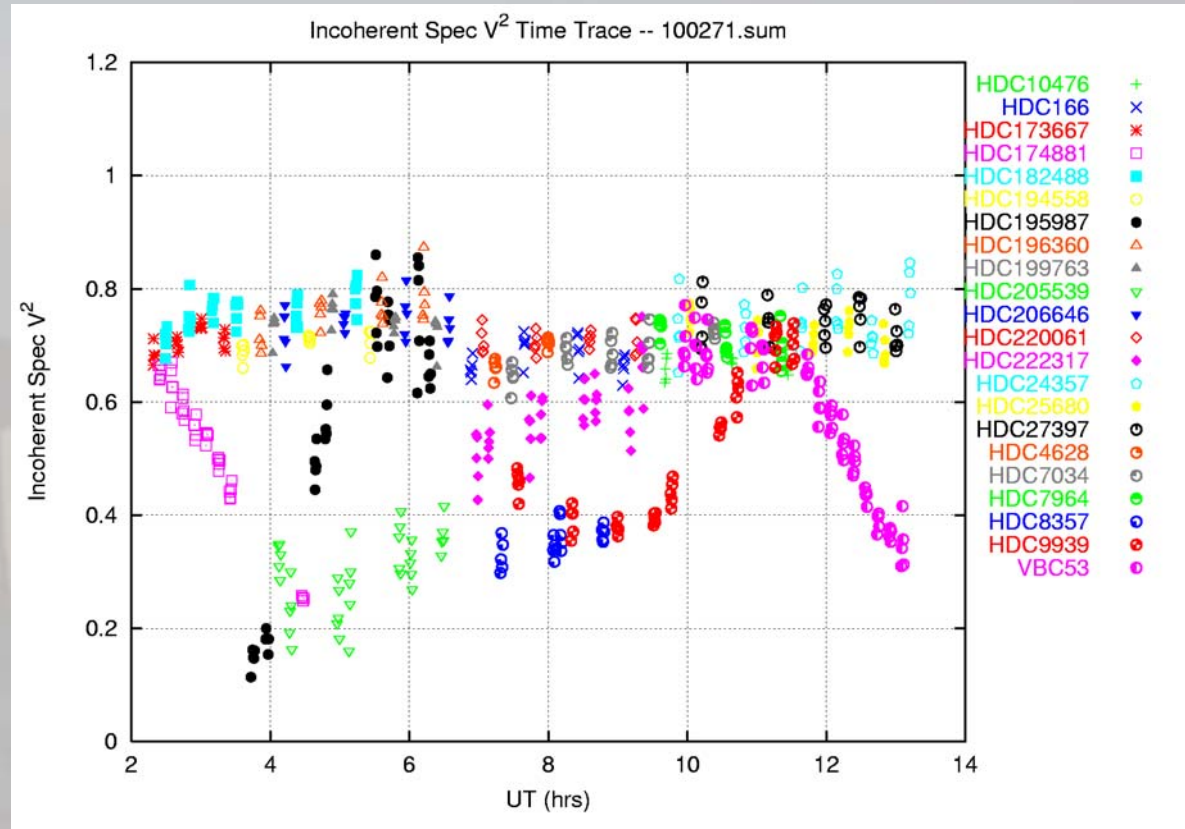
Of Course, Resolved Multiple (e.g. Binary) Stars Make BAD Calibrators
Because They **Greatly** Compound The Modeling Issues

Nature is *Apparently* Fond of Making Stars in Multiple Associations, so
Multiplicity is Something to be Carefully Avoided – But How?

Stellar Multiplicity -- Visibility

Visibility Data Exhibits
Variations From Two
Resolved Components
of Binary System

Tradition (and Logic)
Preclude Use of
Binaries as Calibration
References



$$V_{Binary}^2 = \frac{V_1^2 + V_2^2 r^2 + 2V_1V_2r \cos\left(\frac{2\pi}{\lambda} B \cdot s\right)}{(1+r)^2}$$

Homework: Derive

Stellar Multiplicity -- Prevalence

Our Knowledge of Stellar Multiplicity is Dominated by the Landmark Work of Duquennoy & Mayor 1991

Two out of Three Solar-like Stars Have Stellar Companions

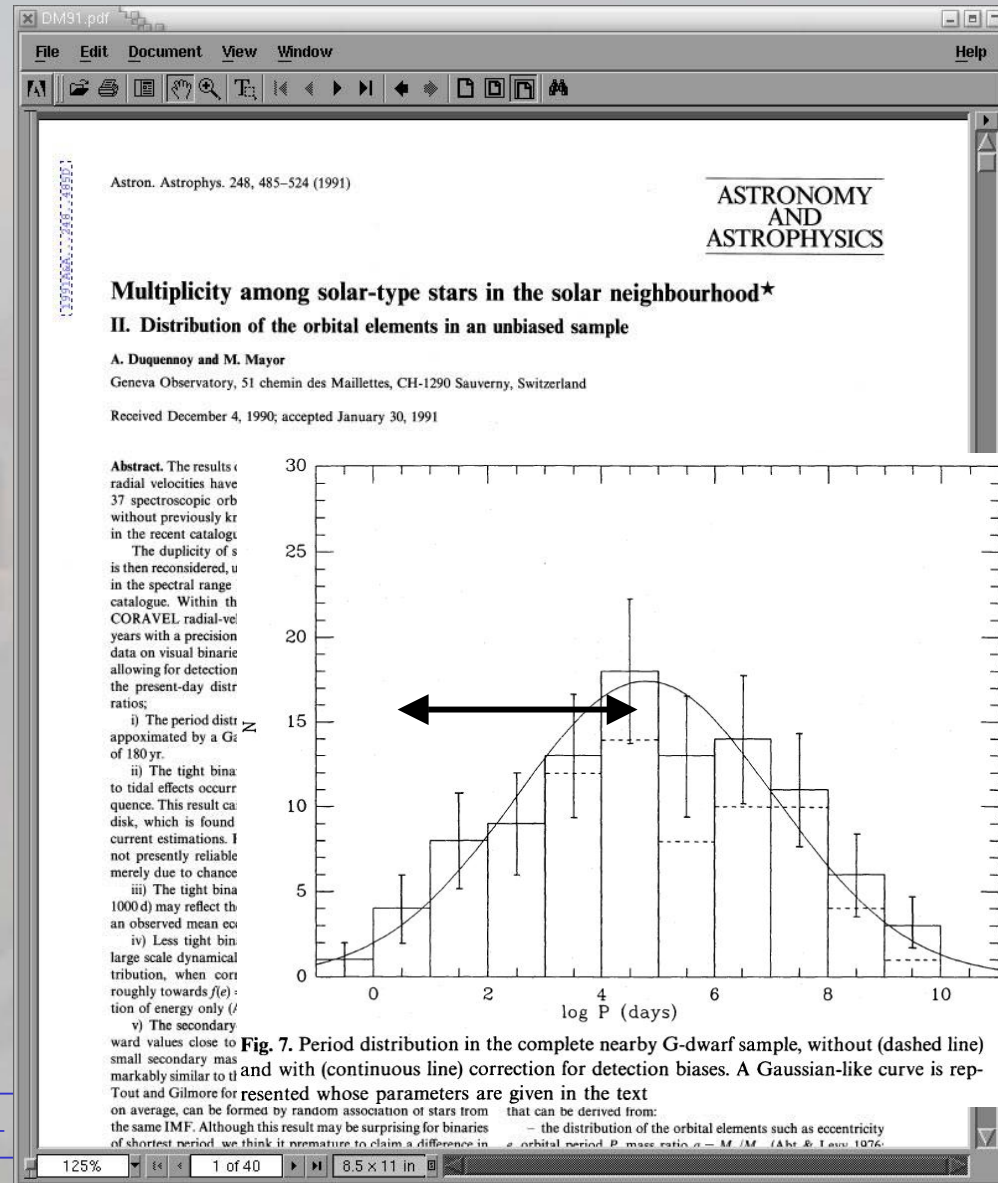
Companion Fraction *Appears* To Increase With Mass (Knowledge Poor Away From Solar Mass)

Companion Fraction Likely Higher in Pre-Main Sequence Phase

Apparently Nature Really Likes to Make Binaries!

For Our Purposes Only a Fraction of The Binaries are Troublesome – **Namely Those Whose Separations Cause Interferometric “Confusion”**

Emphasizes Importance of Vetting Potential Calibrators for Multiplicity



Stellar Multiplicity -- Identification

Identification of Multiplicity in Observation Planning Requires **Synthesis** of Information From **Various** Sources

- SIMBAD
- Binary Catalog Info (e.g. Batten, WDS)
- Astrometric Catalogs – Hipparcos! (Deviations from Simple Five-Parameter Astrometric Model As Indicator of Additional Dynamics)
- Spectral Energy Distribution (you're on your own...)

Consequently We Structure Our Planning Tools Package (e.g. getCal, ASPRO) With This Information Synthesis In Mind

Despite Best Intentions, Some Undetected Multiplicity **Will** Escape Pre-Detection

- **Particularly** True In Relatively Unvetted Sensitivity Space of VLTI (and KI)

Choosing Calibrators (Really Calibration Strategy)

So With These Guidelines in Mind (Small, Single), How Do You Chose Calibrators Given a Target:

This Is Driven By Your Calibration Strategy...

- * Global Instrument & Environment Calibration

“Few” Calibrations Meshed Together into Global Instrument & Environment Model By Functions That Capture Character of Variations => More Science Observatons

Mark III Interferometer (Mozurkewich et al 1991)

- * Local Instrument & Environment Calibration

“Many” Calibrations in Spatial and Temporal Proximity to Science Observation Applied Only Locally => Most Robust With Highly Variable Conditions

PTI (Boden et al 1998), **NPOI** (Hummel et al 1999)

Driven By Instrumental & Environmental Parameters (Namely Temporal & Angular Stability)

Choosing Calibrators (2)

In Either Case The First Step is Sifting Through One or More Astronomical Catalogs to Identify Candidate Calibrators...

The image shows a screenshot of the 'getCal GUI v0.51dev (getCal v2.4pre)' window. The 'Object Designation/Pos' field contains '43_Per'. The 'File' menu is open, showing options like 'No Calibrators', 'LC V', 'LC III', 'LC I', and 'Max Diam (mas)'. The 'Calibrator Search Radius' section includes fields for 'Min V', 'Max V', 'Min K', and 'Max K'. The 'Timing Info' section has 'Timing Display' and 'u-v Display' checked. The 'Palomar (PTI)' section has 'Baseline Selection' checked. The 'Zenith Angle Limit' section has 'Delay Limit' checked. The 'Select Date' section shows 'January', 'day 3', and 'year 2002'. The 'fbol diameters' section has 'Cal Script Composition', 'Parallax', and 'Keck sky fmt' checked. The 'Dispatch' and 'Reset' buttons are visible at the bottom.

The terminal window titled 'getCal Return -- 43_Per' shows the output of the command: `/home/bode/iscSoftware/src/tools/planning/getCal/getCal-2.4/getCal -targetName 43_Per -lcl`. The output is as follows:

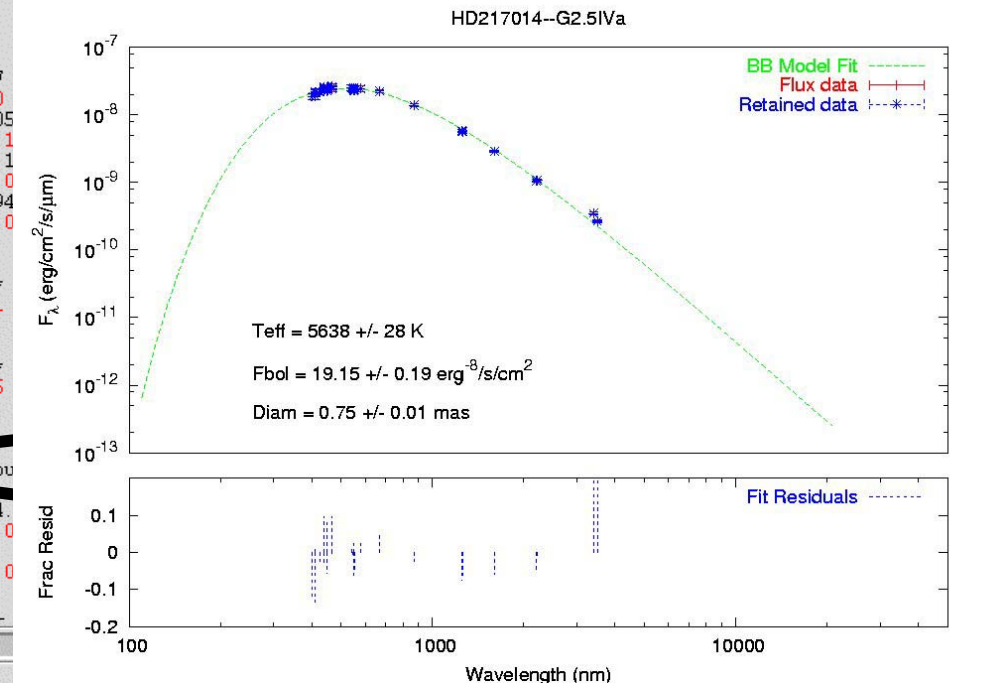
```
### GUI catalog from getCal v2.4pre ###
# Resolving target 43 Per via SIMBAD
# target HD 24546
# Simbad Search HD 24546: Type: Spectroscopic binary F5IV V=5.287 + 43 Per ** S 440AP
HDC24546 03 56 36.522 +50 41 43.371 0.149 -0.128 5.3 4.2 F5IV 0.0 xxxx xxxc trg
# Simbad Search HD 19373: Type: High proper-motion Star G0V V=4.05 * iot Per
HDC19373 03 09 04.020 +49 36 47.799 1.948 -0.092 4.0 2.6 G0V 7.7 1.07+/-0.3 cal HDC24546
# Simbad Search HD 20677: Type: Variable Star A3V V=4.947 SV+ ZI 181 * 32 Per * l Per
HDC20677 03 21 26.559 +43 19 46.743 -0.083 -0.000 5.0 4.8 A3V 9.5 0.41+/-0.0 cal HDC24546
# Simbad Search HD 20675: Type: High proper-motion Star F6V V=5.947
HDC20675 03 21 52.533 +49 04 15.257 0.276 -0.063 5.9 4.7 F6V 5.8 0.34+/-0.2 cal HDC24546
# HIP 16826 (HD 22192) has his variability flag set (2)
# with 0.033 mag scatter in 77 observations
# Simbad Search HD 22192: Type: Emission-line Star B5Ve V=4.310 * psi Per * 37 Per EM*
HDC22192 03 36 29.379 +48 11 33.481 0.032 -0.028 4.3 4.7 B5Ve 4.1 0.25+/-0.2 cal HDC2454
# HIP 19343 (HD 25940) has his variability flag set (1)
# with 0.007 mag scatter in 84 observations
# Simbad Search HD 25940: Type: Emission-line Star B3Ve V=4.003 * c Per * 48 Per EM* MW
HDC25940 04 08 39.691 +47 42 45.046 0.030 -0.033 4.0 4.5 B3Ve 3.6 0.30+/-0.1 cal HDC2454
# HIP 20070 (HD 26961) has his variability flag set (1)
# with 0.020 mag scatter in 90 observations
# HIP 20070 (HD 26961) has his multiple component flag set to 0
# Warning: the 0 designation indicates an orbital solution was found
# with photocentric SMA 5.09 mas, 701.7600 day period
# Simbad Search HD 26961: Type: Ellipsoidal variable Star A2V V=4.598 V+ b Per * b Per
HDC26961 04 18 14.618 +50 17 43.808 0.073 -0.056 4.6 4.6 A2V 3.5 0.35+/-0.3 cal HDC24546
# Simbad Search HD 27084: Type: Star in Cluster A7V V=5.40
HDC27084 04 19 13.239 +50 02 55.302 0.098 -0.059 5.5 5.0 A7V 3.7 0.28+/-0.2 cal HDC24546
# HIP 21730 (HD 29316) has his multiple component flag set to C
# the C designation indicates solutions were found for individual components
```

Choosing Calibrators (3)

Choosing Appropriate Calibrators From The Candidate List

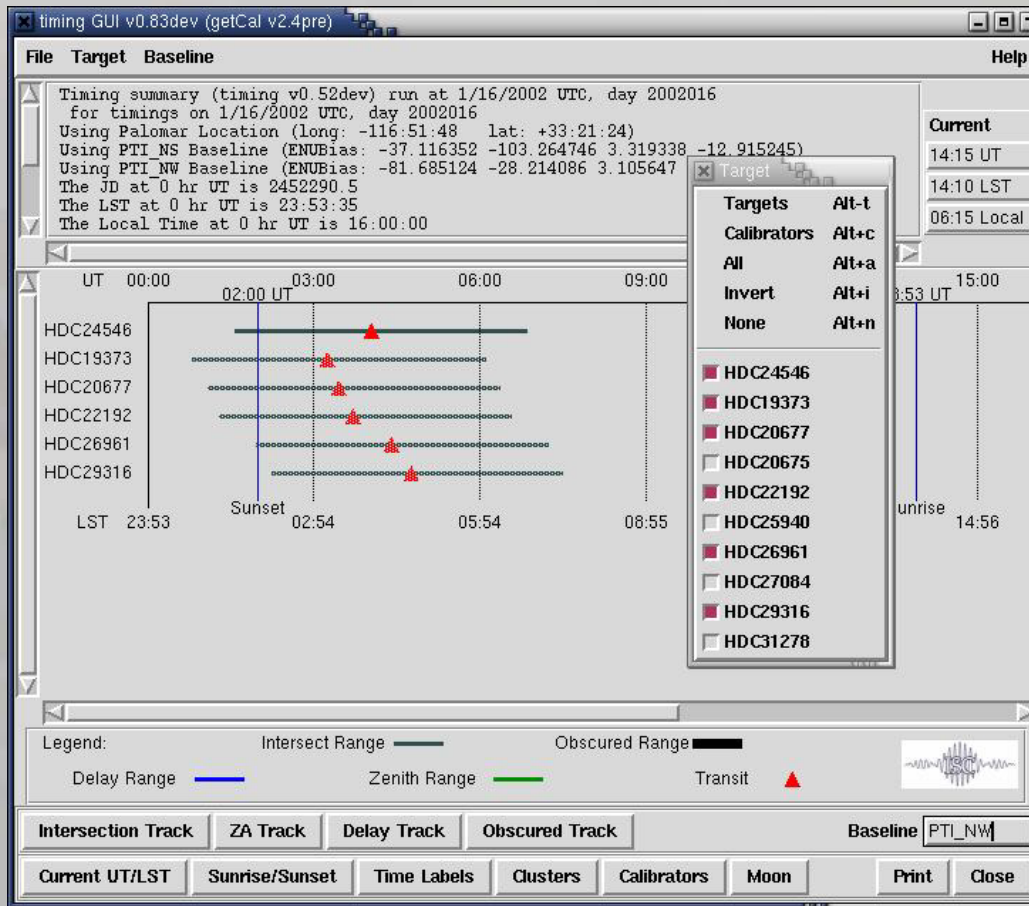
```
getCal Return -- 43_Per
/home/bode/iscSoftware/src/tools/planning/getCal/getCal-2.4/getCal -targetName 43_Per -lcl

### GUI catalog from getCal v2.4pre ###
# Resolving target 43 Per via SIMBAD
# target HD 24546
# Simbad Search HD 24546: Type: Spectroscopic binary F5IV V=5.287
HDC24546 03 56 36.522 +50 41 43.371 0.149 -0.128 5.3 4.2 F5IV 0.0
# Simbad Search HD 19373: Type: High proper-motion Star G0V V=4.05
HDC19373 03 09 04.020 +49 36 47.799 1.948 -0.092 4.0 2.6 G0V 7.7 1
# Simbad Search HD 20677: Type: Variable Star A3V V=4.947 SV* ZI 1
HDC20677 03 21 26.559 +43 19 46.743 -0.083 -0.000 5.0 4.8 A3V 9.5 0
# Simbad Search HD 20675: Type: High proper-motion Star F6V V=5.94
HDC20675 03 21 52.533 +49 04 15.257 0.276 -0.063 5.9 4.7 F6V 5.8 0
# HIP 16826 (HD 22192) has his variability flag set (2)
# with 0.033 mag scatter in 77 observations
# Simbad Search HD 22192: Type: Emission-line Star B5Ve V=4.310 +
HDC22192 03 36 29.379 +48 11 33.481 0.032 -0.028 4.3 4.7 B5Ve 4.1
# HIP 19343 (HD 25940) has his variability flag set (1)
# with 0.007 mag scatter in 84 observations
# Simbad Search HD 25940: Type: Emission-line Star B3Ve V=4.003 +
HDC25940 04 08 39.691 +47 42 45.046 0.030 -0.033 4.0 4.5 B3Ve 3.6
# HIP 20070 (HD 26961) has his variability flag set (1)
# with 0.020 mag scatter in 90 observations
# HIP 20070 (HD 26961) has his multiple component flag set (2)
# Warning: the O designation indicates a variable solution was found
# with photocentric S.P. 5.5 mas, 701.7600 day period
# Simbad Search HD 26961: Type: Ellipsoidal variable Star A2V V=4.6
HDC26961 04 18 14.618 +50 17 43.808 0.073 -0.056 4.6 4.6 A2V 3.5 0
# Simbad Search HD 27084: Type: Star in Cluster A7V V=5.40
HDC27084 04 19 13.239 +50 02 55.302 0.098 -0.059 5.5 5.0 A7V 3.7 0
# HIP 21730 (HD 29316) has his multiple component flag set to C
# the C designation indicates solutions were found for individual
```



Choosing Calibrators (4)

And Laying Out an Observing Plan...



Observing Targets and Calibrators: Practical Considerations

How **Many** Calibrators Do You Need?

- Only **One** – If You Trust It...And **KNOW** It's Diameter!!!
- At Least **Two** If Both Objects Are New To Your Observing Program
(What if Multiplicity Previously Undetected?)
- Probably **Three Or More** If Objects Are Relatively Unvetted (KI & VLTI Sensitivity Regime)
- Common (but **Not Required**) To Identify a Primary Calibrator and Secondary Calibrators (That is – One Calibrator You Will Observe/Rely On Most)

How **Often** Should I Observe The Calibrators?

- Equal-Variance Rule Of Thumb: For *Local* Calibration You Should Spend Equal Time on Target and Calibrators (Minimum Variance)
- For Global Calibration Schemes: Depends Entirely on Residual Noise Covariance Functions With Sky Position and Time (But Can Be Less Than One-to-One With the Target)

More Practical Considerations

How Do I **Estimate** Calibrator Angular Diameters?

- I've Given You One Answer – Bolometric Flux and Effective Temperature – This is the Most Important Method
- IRFM – Infrared Flux Method (Blackwell et al.)
- Maximize Inter-consistency Among Calibrators

What Happens If I Have the Calibrator Angular Diameters Wrong?

- Systematic (Correlated) Errors in Calibrated Visibilities (*Homework: How Large?*)
- Critical To Consider (Correlated Systematic Errors) in Final Scientific Reduction!

One Last Practical Consideration Slide: Operation in Thermal Infrared

VLTI MIDI & KI 10 μm Combination Represents New Operational Space (and **Probably** New Calibration Challenges)

Atmosphere Known To Be More “Dynamic” At These Wavelengths => Higher Target/Calibrator Chopping Frequency?

Predicting Angular Sizes at 10 μm – Circumstellar Material?

Many Stars (i.e. Evolved Stars) are Known To Be Losing Mass at Significant Rates ($\sim 10^{-4} M_{\text{sun}}/\text{yr}$)

This Material is Warm (~ 100 's K) and Consequently Remains Emissive in Thermal Infrared

Key Tracer Would Be Thermal Infrared Excess in the Spectral Energy Distribution (SED)

*Likely Added Emphasis on Choosing **Main Sequence** Calibrators*

Summary

Calibration Observations Are Necessary To Characterize Instrument and Environment Limitations

Bright Point Sources Are Optimal Calibrators – And **Don't** Exist
Consideration of Calibrator Angular Diameters

Effectively Single-Stars Are The Only Appropriate Choice
Determining Which Stars are Effectively Single

Pulling This All Together In An Experiment Strategy
Instrument Stability is Critical Limitation