Finding Calibrator Stars

Andy Boden
Interferometry Science Center
California Institute of Techology

http://isc.caltech.edu

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

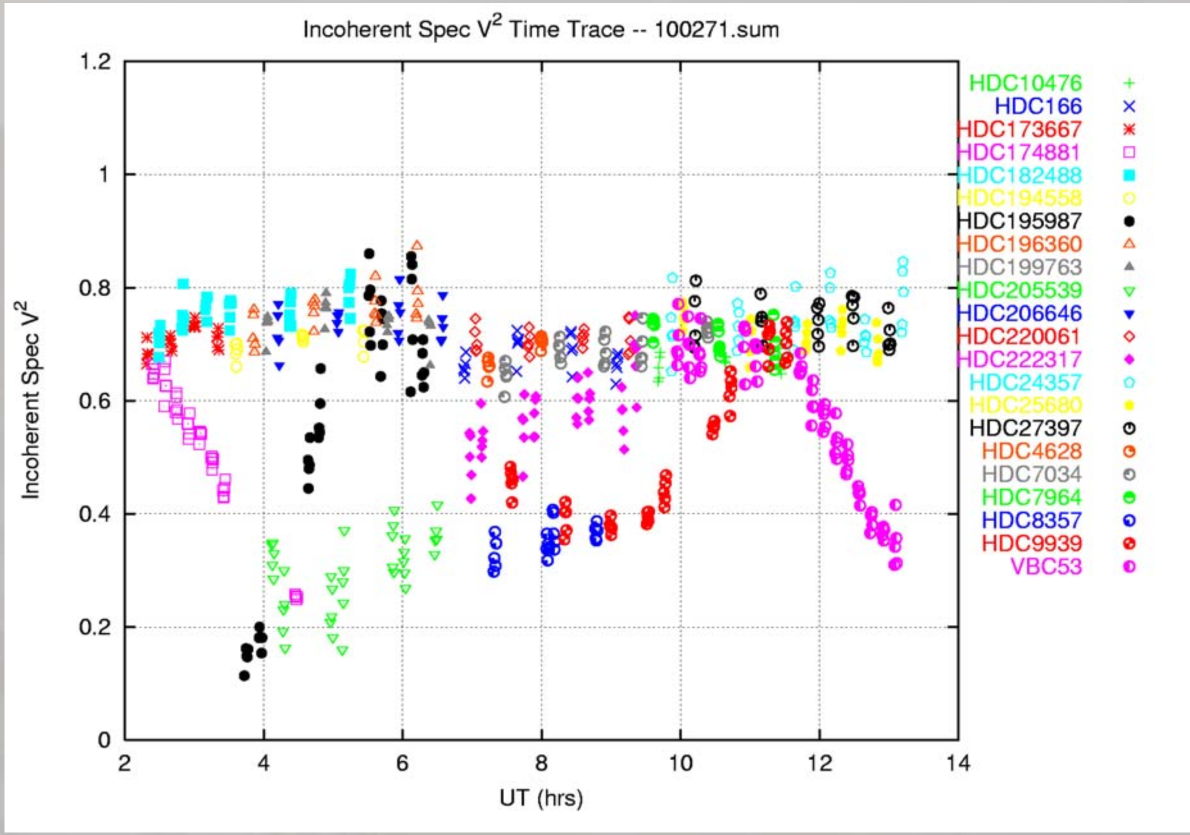
=> Calibrator Measures In-Coherence of Interferometer

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

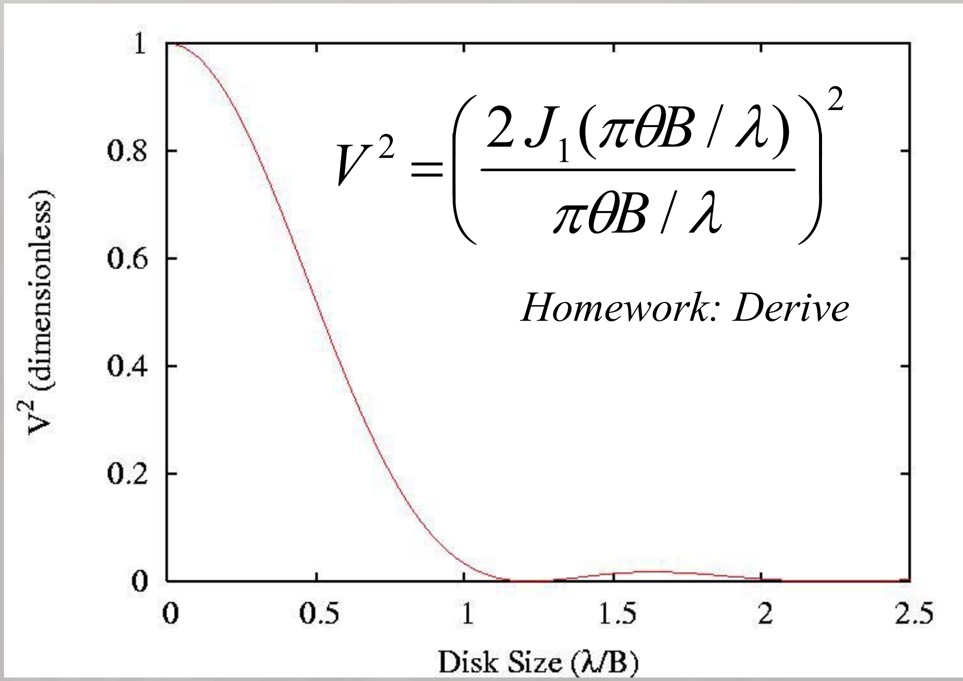
$$SNR \propto NV^2$$

- 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

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

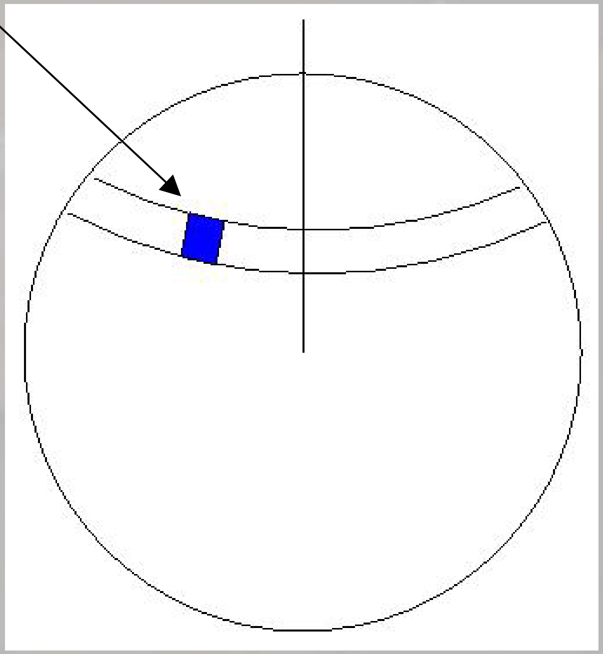
So How Big Do Stars Appear Anyway?

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

One Solution is to "Know" the Linear Size and Distance

$$\theta_{sun} = d_{sun} / D$$

$$\cong [0.01 AU] / [10\, pc] = 10^{-3}\, arc\sec \equiv 1\, mas$$



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

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

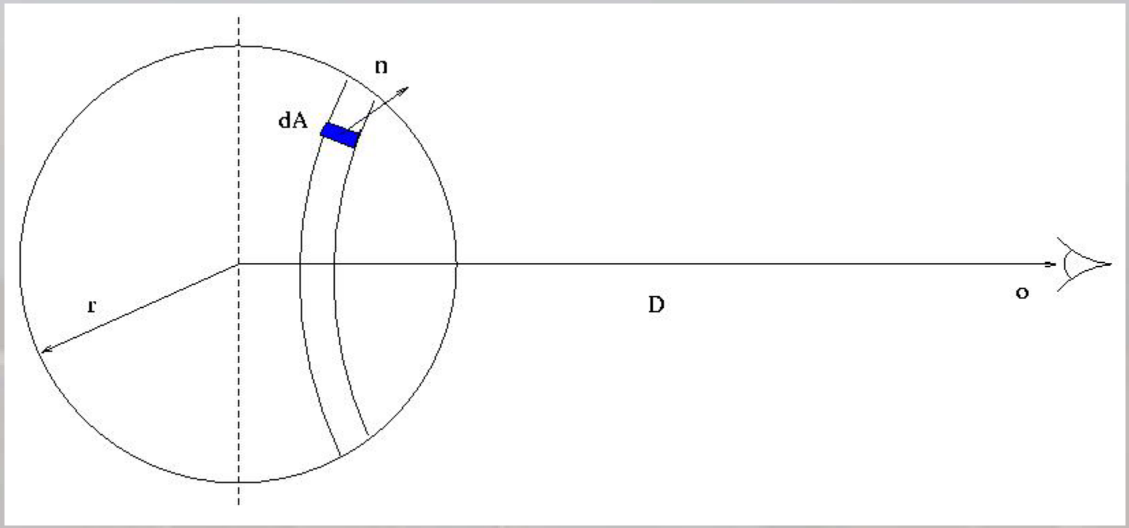
Angular Sizes of Stars (2)

Radiation per unit star surface area into unit solid angle:

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

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 Distance D:

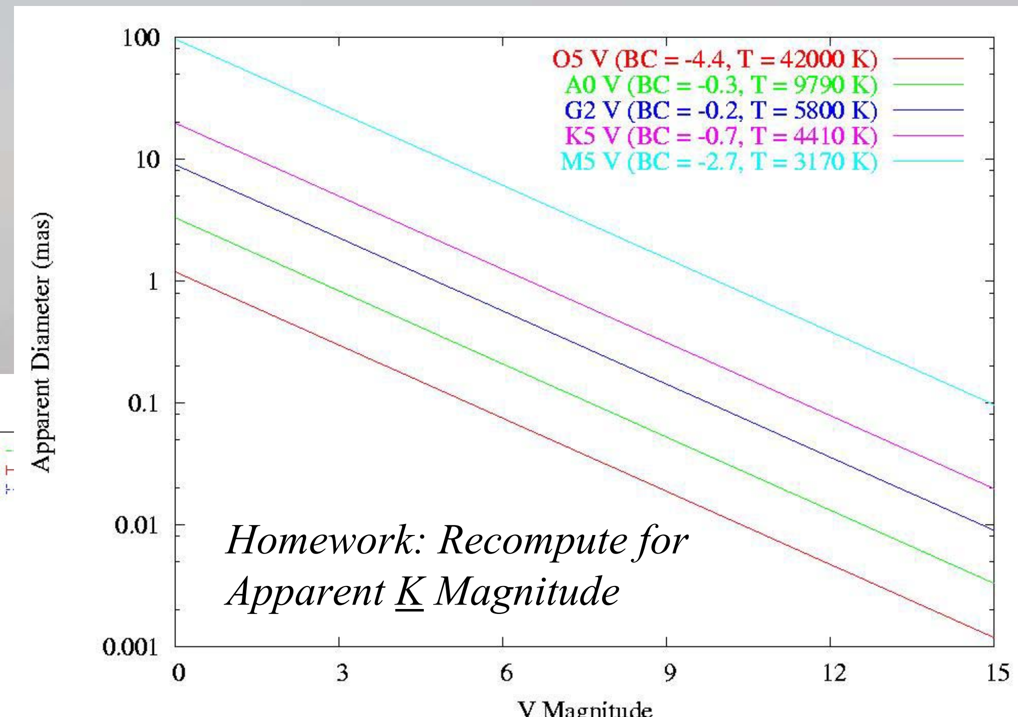
$$F_{Bol} = \int_{2\pi} dA \frac{\sigma T_{eff}^4}{\pi} \cos\theta / D^2 = \frac{r^2}{\pi D^2} \sigma T_{eff}^4 \int_{2\pi} d\theta\, d\phi \sin\theta \cos\theta$$

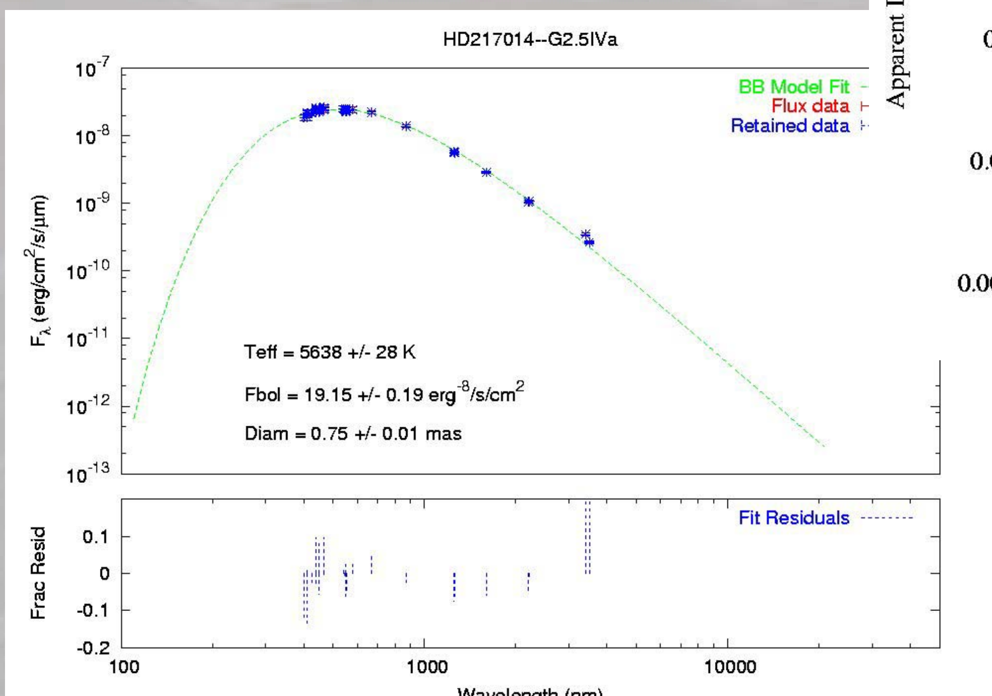
$$= \frac{1}{2} \frac{4r^2}{D^2} \sigma T_{eff}^4 \left[\frac{1}{2} \sin^2\theta \right]_0^{\pi/2} = \frac{1}{4} \Theta^2 \sigma T_{eff}^4$$

Angular Sizes of Stars (3)

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

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





- 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

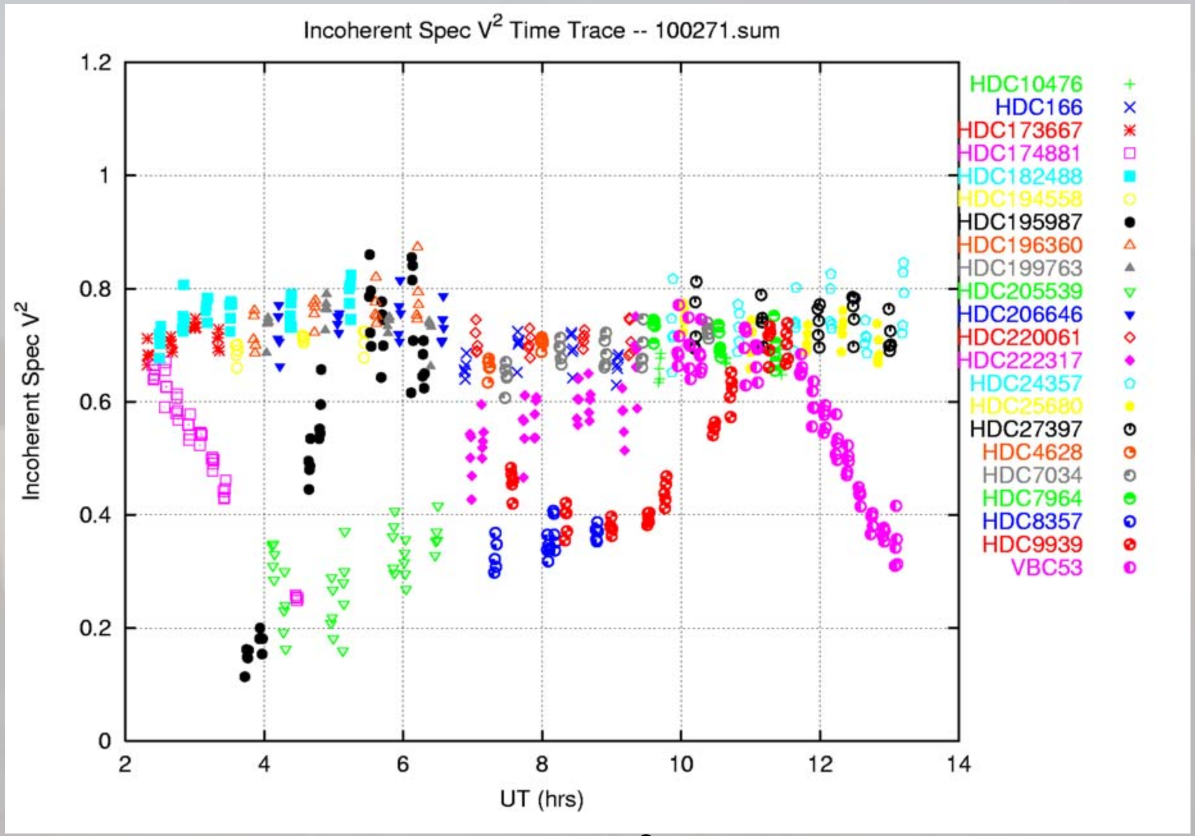
Of Course, Resolved Multiple (e.g. Binary) Stars Make BAD Calibrators Because They Greatly Compound The Modeling Issues

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

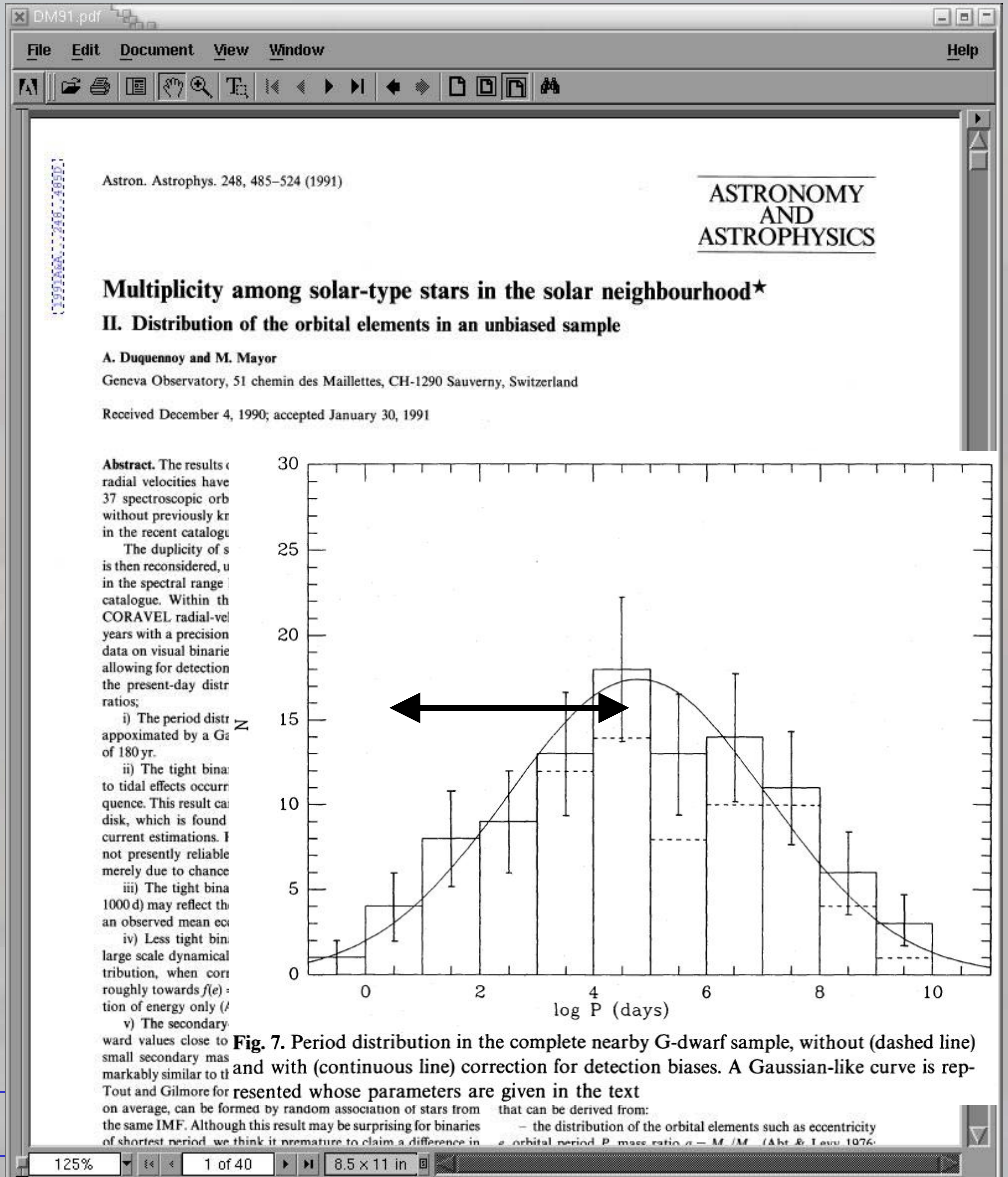


$$V^2_{Binary} = \frac{V_1^2 + V_2^2\, r^2 + 2\,V_1 V_2 r \cos(\frac{2\pi}{\lambda}\; B \bullet s)}{(1+r)^2}$$

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



Astron. Astrophys. 248, 485–524 (1991)

ASTRONOMY AND ASTROPHYSICS

Multiplicity among solar-type stars in the solar neighbourhood★

II. Distribution of the orbital elements in an unbiased sample

A. Duquennoy and M. Mayor

Geneva Observatory, 51 chemin des Maillettes, CH-1290 Sauverny, Switzerland

Received December 4, 1990; accepted January 30, 1991

Fig. 7. Period distribution in the complete nearby G-dwarf sample, without (dashed line) and with (continuous line) correction for detection biases. A Gaussian-like curve is represented whose parameters are given in the text

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

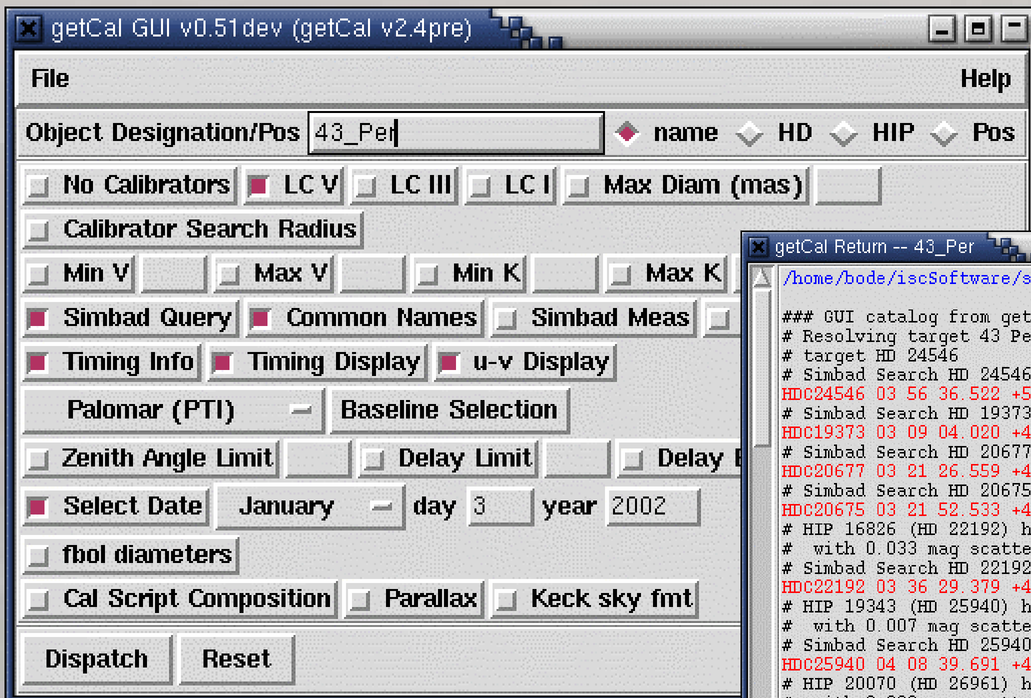
  "Many" Calibrations in Spatial and Temporal Proximity to Science Observation Applied Only Locally => Most Robust With Highly Variable Conditions

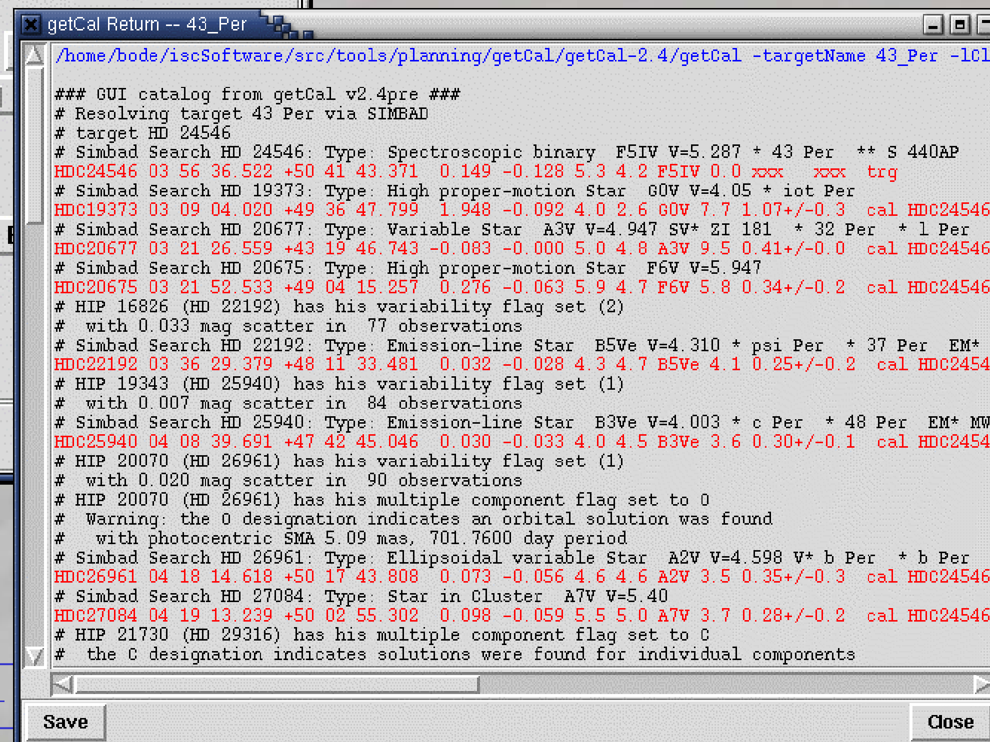
  PTI (Boden et al 1998)**, NPOI** (Hummel et al 1999)

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

Choosing Calibrators (2)

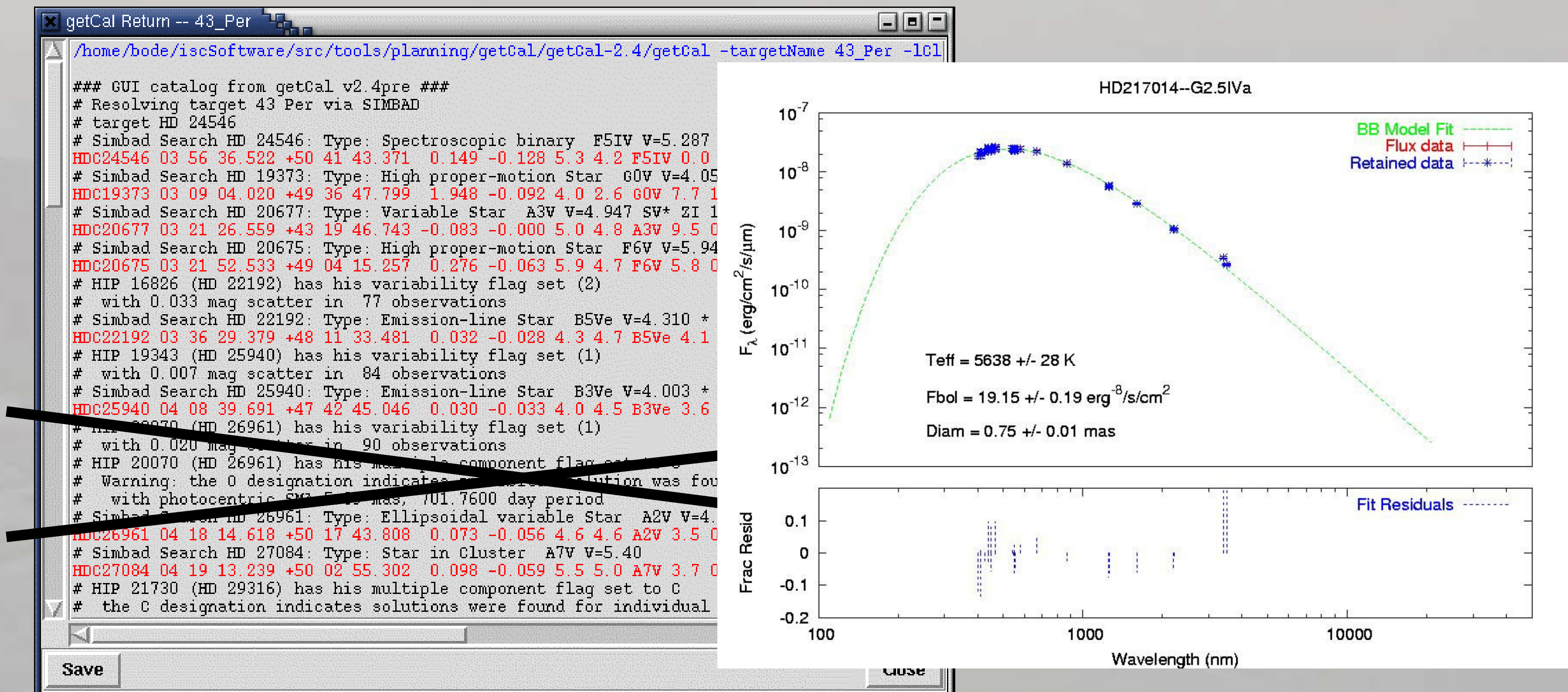
In Either Case The First Step is Sifting Through One or More Astronomical Catalogs to Identify Candidate Calibrators…





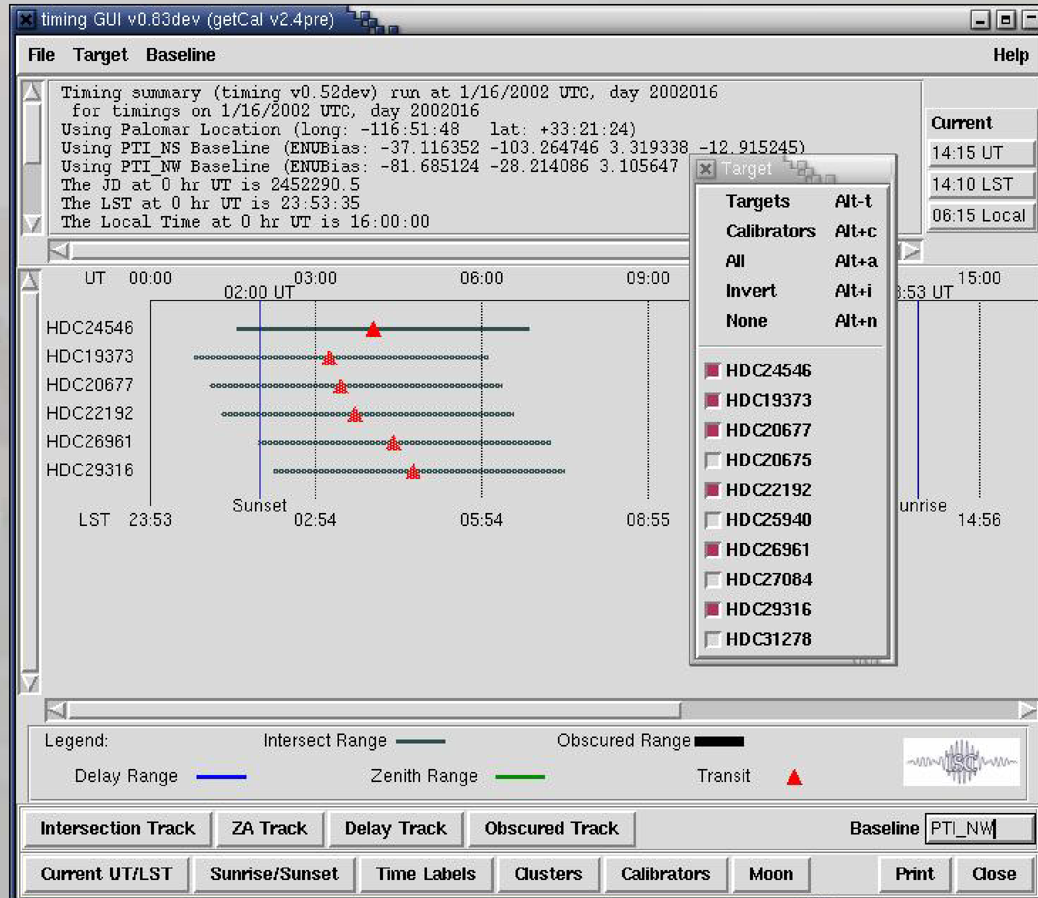
Choosing Calibrators (3)

Choosing Appropriate Calibrators From The Candidate List



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 <u>KNOW</u> 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 (~ 10^{-4} M_{sun}/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