Imaging Stars with an Optical Interferometer and Polarimeter*

Nick Elias *et al.***
NRAO/Socorro
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*Described by Bob Koch as "courageous"

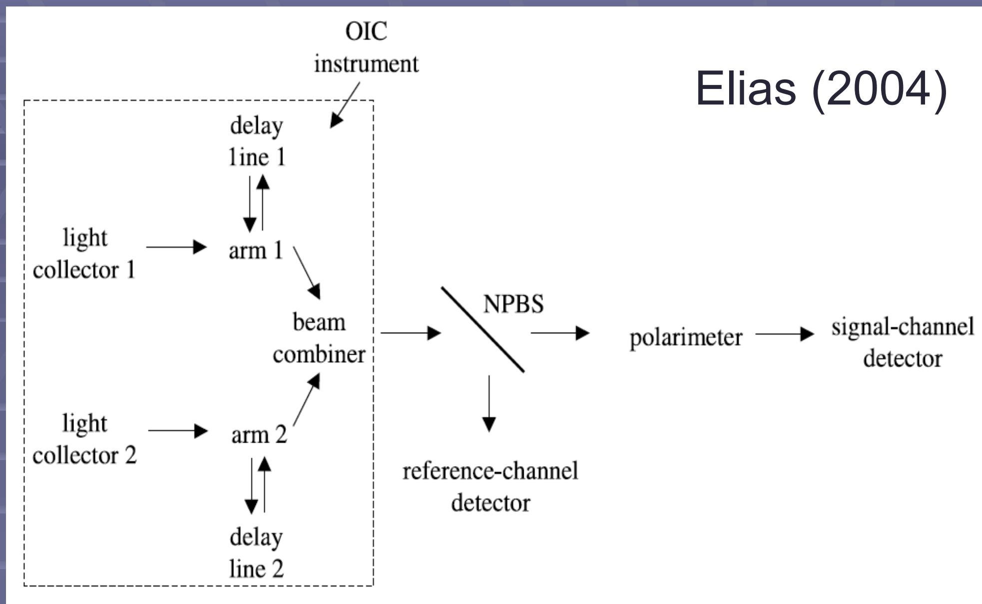
**S.S. Edel, D. Mozurkewich, C.E. Jones, F.E. Mackay, A.M. Jorgensen, H.R. Schmitt

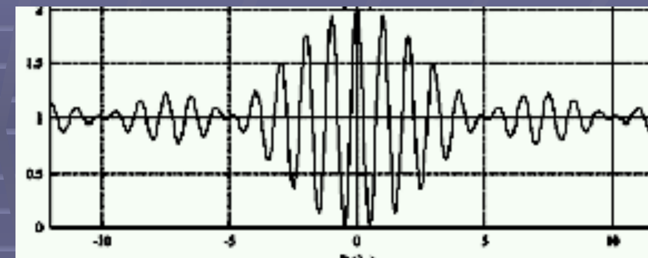
Papers with Bob

- Polarimetric measures of selected variable stars
  - Elias II, N.M. Koch, R.H., Pfeiffer, R.J. 2008, A&A 489, 911
- Photospheric Spots and a Chromospheric Plage on V523 Cassiopeiae
  - Elias II, N.M. and Koch, R.H. 2000, AJ 120, 1548
- The long-term elliptical polarization behavior of Beta Lyrae
  - Elias II, N.M., Koch, R.H., Holenstein, B.D. 1996, BAAS 28, 913
- UBVRI polarization of RS CVn-type binaries
  - Scaltriti, F., Piirola, V., Coyne S.J., G.V., Koch, R.H., Elias II, N.M., Holenstein, B.D. A&AS 102, 343
- Polarizing gas at small optical depths around ALGOLS
  - Koch, R.H., Elias II, N.M., Corcoran, M.F., Holenstein, B.D. 1989, SSRv 50, 63

Look for Bob on facebook: Robert H. Koch (Astronomer)

Simplified OIC/OIP Concepts





$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$\varphi = 2 \pi \kappa d$

- OIC: Instrument maps Young's experiment to delay space
- OIC: Instrument modulates in delay and measures scalar visibilities, which are Fourier components of image
- OIP: Polarimeter and modulates V and φ

➔Estimate complex Stokes visibility vector

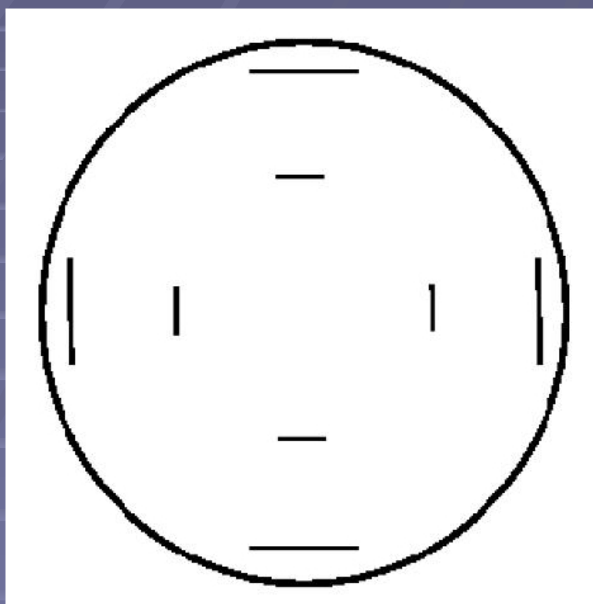
➔Fit visibility models and/or Fourier transform for Stokes images

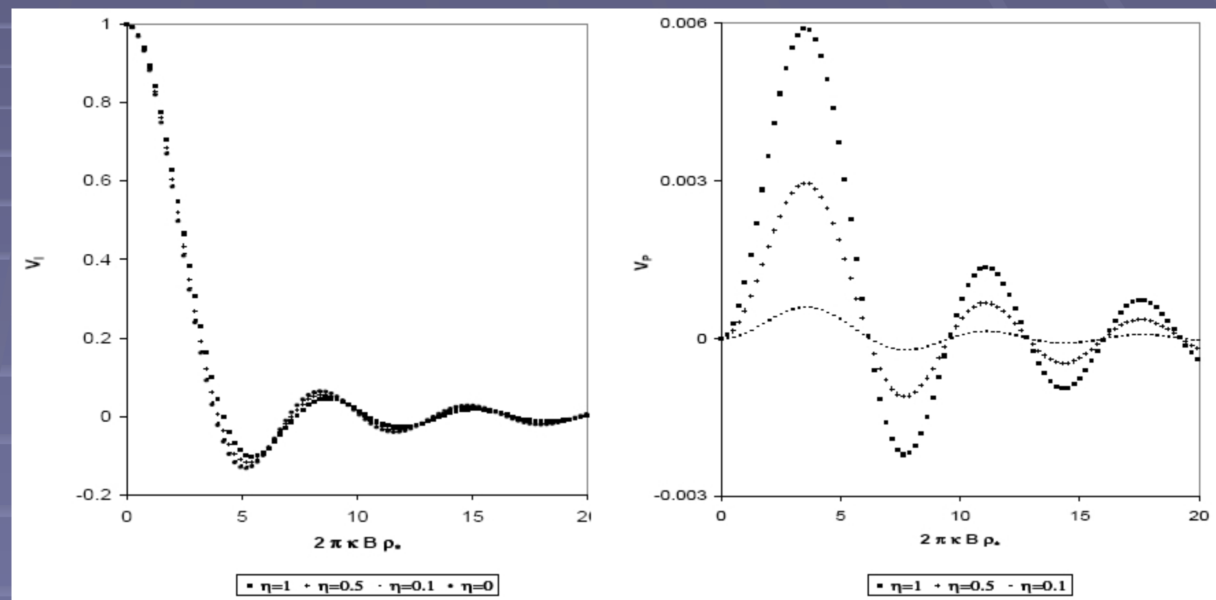
OIP History

- In a nutshell
  - OIC possible because of small source/instrumental polarization
    - Scalar electric fields and visibilities ←→ Stokes I visibilities
    - Very good serendipitous science
  - I started thinking about full-Stokes OIP immediately after I got my PhD (1990)
  - Jacques Beckers published the first OIP paper in SPIE about the same time
  - I and several others have been steadily thinking about OIP instruments and algorithms "in the background"
    - Polarimetry (hard) + Interferometry (hard) → really hard!
- The pieces are coming together
  - **Astrophysics:** more polarization and visibility modeling
  - **Instrumentation:** low-noise CCDs, GI2T, SUSI, CHARA/VEGA
  - **Algorithms & Software:** coherent averaging, telescope-based calibration (!), wideband CASA (NRAO interferometer imaging software) calibration and imaging, CASA visualization and editing

“Chandrasekhar” Atmosphere

- “Toy” case: early star & Thomson scattering (Elias 2004)
  - Simple, closed form visibilities



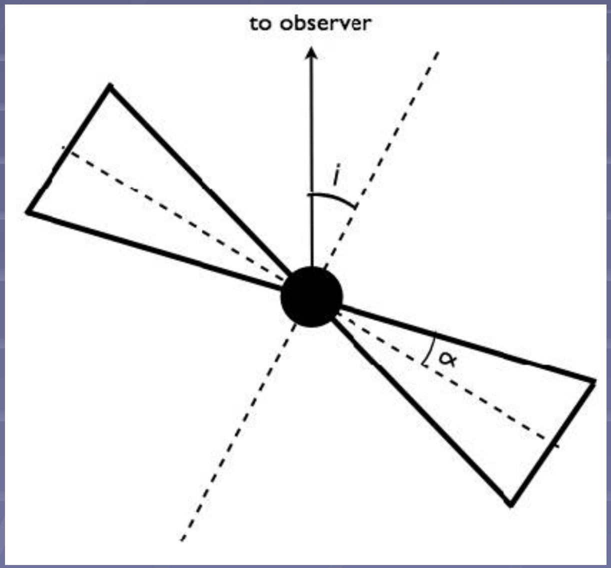


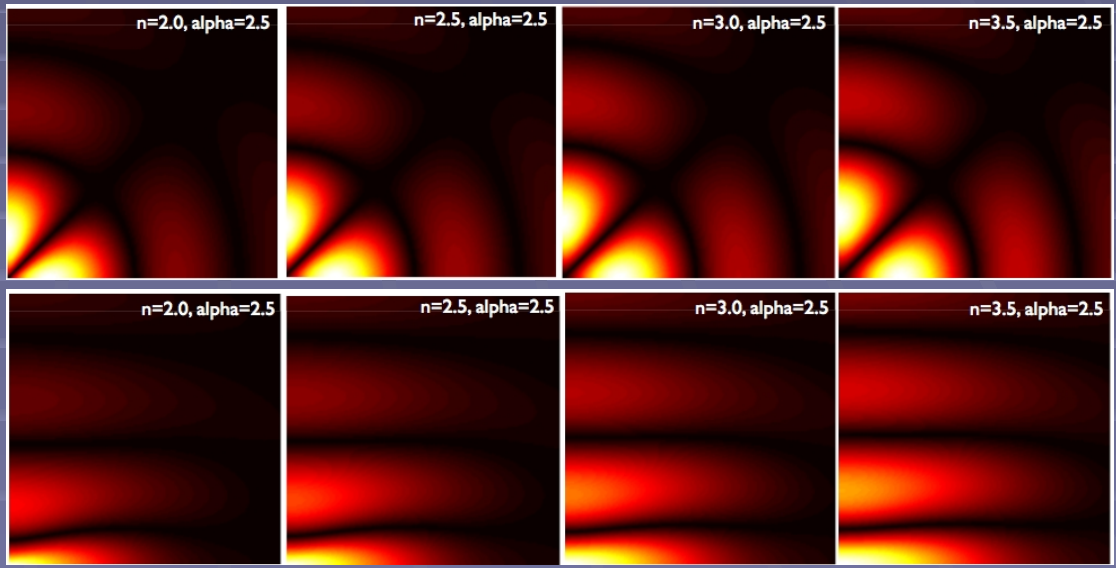
➔ Even calibrators (i.e., boring stars) become interesting!

➔ Studies of other scattering mechanisms (e.g., dust)

Be Stars

- "Poster child" case: B star with extensive ionized disk
- Lots of observations in the literature (Quirrenbach *et al.* 1997)
  - Optical polarimetry (continuum) → ~ shape and orientation of envelope
  - Hα interferometry (line) → ~ size and orientation of envelope



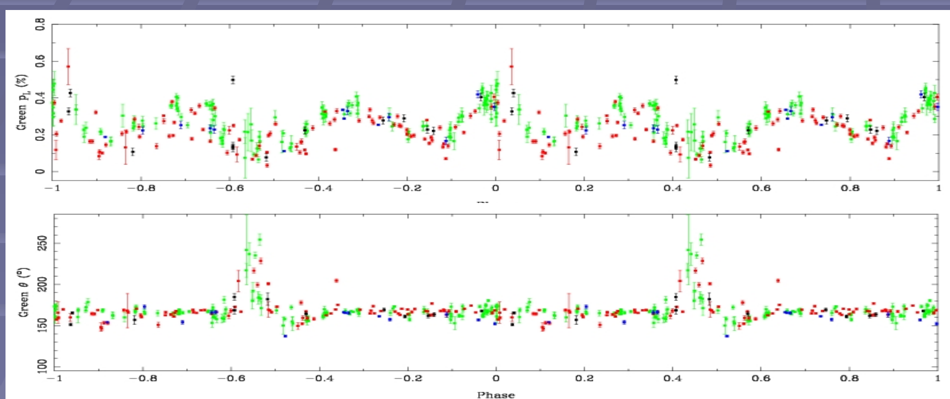


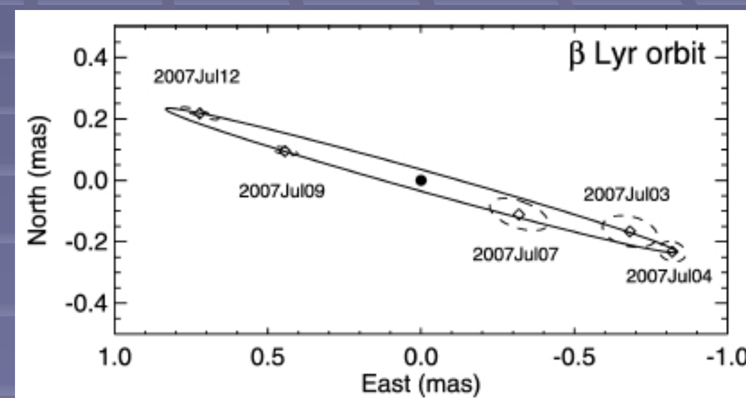
→Mackay *et al.* (2009) created Be star models and visibilities

→Carol Jones and students creating multiwavelength models

Mass-Transferring/Losing Binaries

- Excellent example for use case: β Lyr
- Many observations at multiple wavelengths with multiple techniques
  - Polarimetry (CBE; Elias *et al.* 1996)
  - Optical interferometry (stars; Zhao *et al.* 2008)



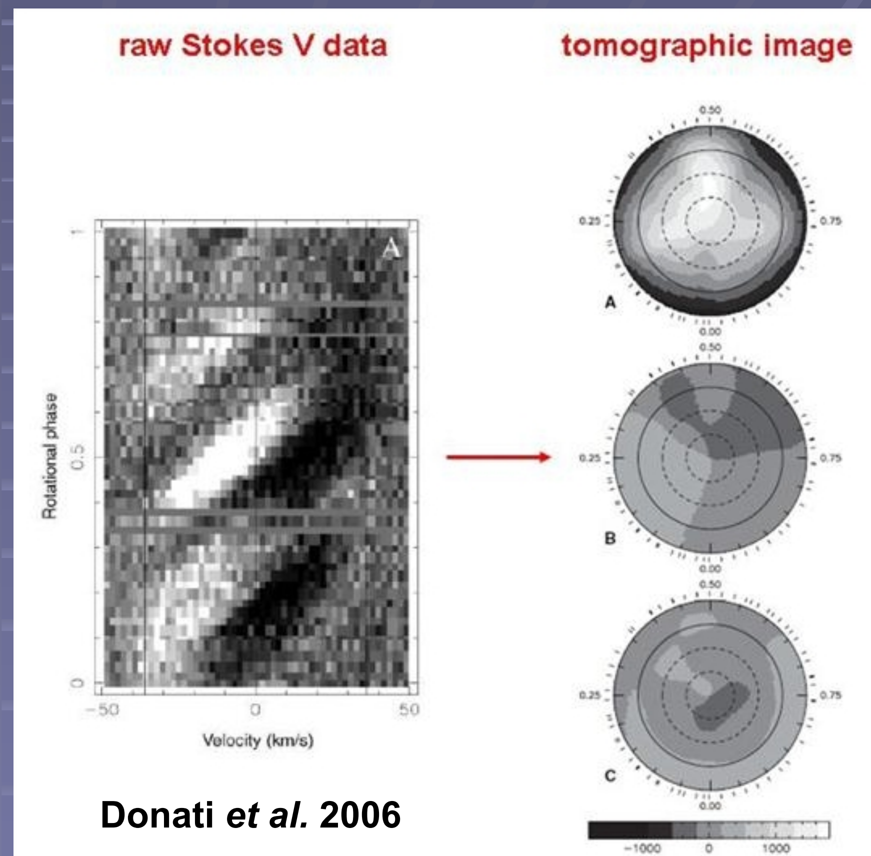


➔Lomax *et al.* (2011) combining modern spectropolarimetry with archival spectropolarimetry and filter polarimetry

➔OIP simulations possible with extensive archival data?

Magnetically Induced Polarization

- How do fully convective late-type stars generate strong magnetic fields?
- Could be different from solar-type stars …
- Zeeman splitting measurements (Stokes V) versus spin phase
- Produce tomographic images and fits
- Hard for OIP: Faint

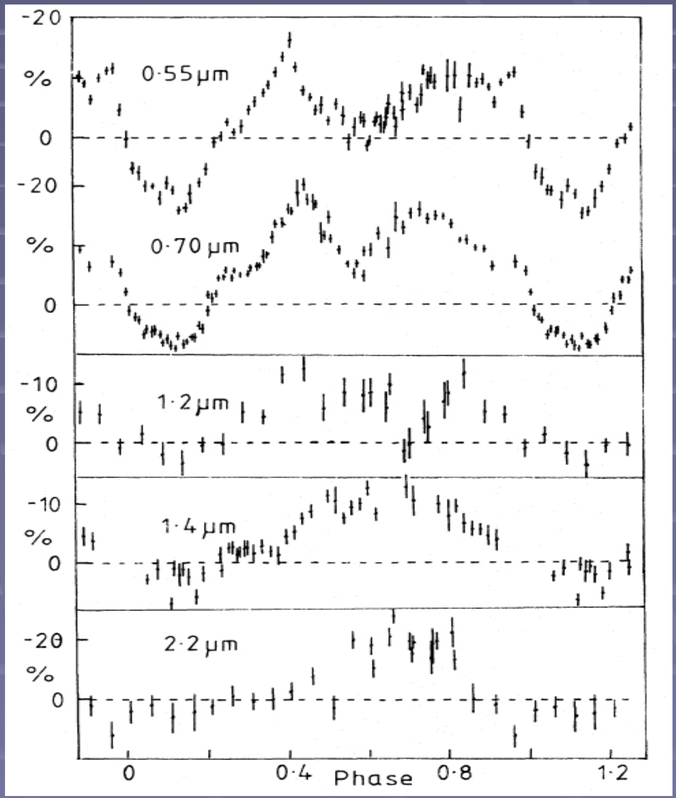


Donati *et al.* 2006

AM Her Binaries

- Late-type star & WD
- Semi-detached
- B ~ 10^6 G at WD poles
- Polar stream accretion
- Cyclotron emission
- Phase dependence due to orientation of accretion poles
- Large polarization, curve depends on wavelength
- Hard for OIP: Faint

AM Her (Stokes V)



Bailey et al. (1984)

Other Use Cases

- YSOs
  - Disks and jets
  - A few bright objects
- Red giants and supergiants
  - Stars, shells, disks
  - There a good number of bright sources
- LBVs
- …

Instrument Requirements

- Errors (from science use cases)
  - Systematic instrumental polarization errors ~ a few times 10^{-4}
  - Random scalar visibility errors ~ a few times 10^{-4}

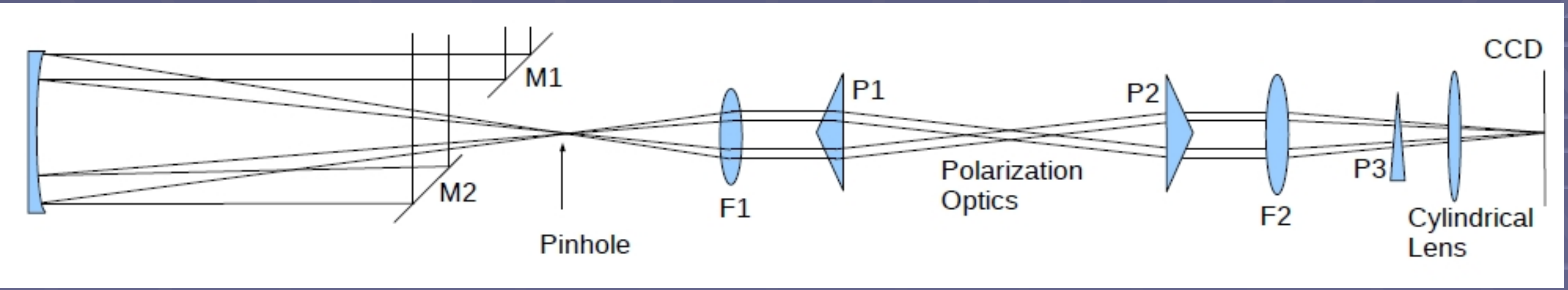
➔ Optics:
  - Spatial filtering
  - Minimal reflecting optics, none after the polarimeter
  - Both beams go through the same polarimeter

➔ Full-Stokes polarimeter:
  - No moving parts, minimal heat input
  - Sequential cycles through polarimeter states → simple
  - Minimal beam wander as a function of polarimeter state

➔ Existing external group delay fringe tracker:
  - Same wavenumber range as polarization beam combiner
  - Used for off-line phase correction and normalization

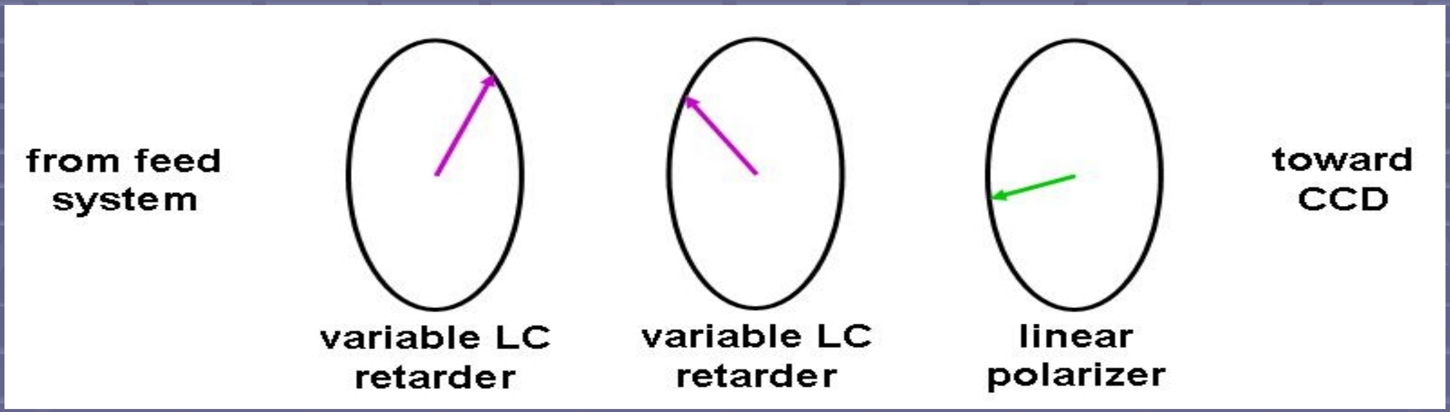
➔ Coherent averaging and phase bootstrapping:
  - Disperse fringes onto a low read-noise CCD
  - Expandable to multiple baselines

Strawman Instrument Design



- Dave Mozurkewich "sequential" design
- Quite simple!
  - Collimated light from feed system sent to focused by parabola
  - The pinhole acts as a spatial filter
  - Glass components straddle polarimeter
  - Spectrally dispersed by a prism
  - Focused onto a CCD for fringe detection
- An advanced systems engineering study is required

Strawman Polarimeter Design

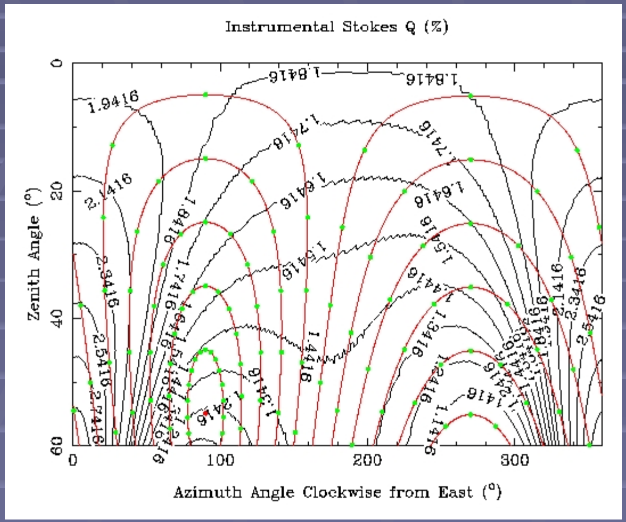


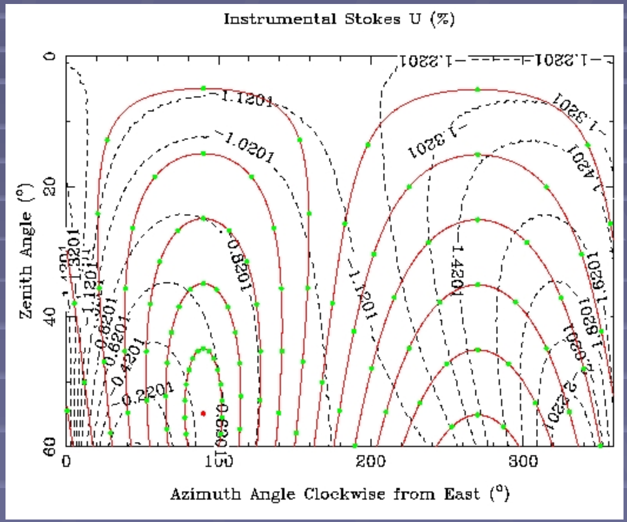
- Nick Elias "sequential full-Stokes" design
  - Classical polarimeters obtain measurement errors < 10^{-4} (with normalization)
  - Different from "simultaneous full-Stokes" design typical at radio λλ
- Two full-wave retarders: Vary one, fix or slowly vary the other
- Fixed linear polarizer
- Studies underway to optimize singular matrix of fit:
  - Orientation of axes
  - Retardance driving pattern
  - Get away with only one full-wave retarder or two half-wave retarders?
  - Wollaston polarizer to regain lost light → redesign beam combiner?

Algorithms and Software

- Instrumental Polarization
  - Done: Some feed system modeling (Elias *et al.* 2008)
  - TBD: OIP calibrator transfer algorithms and/or model fitting
  - TBD: Shoe-horn OIP calibration into CASA telescope based calibration tables (Depolarization issues? Stability requirements?)
- Coherent Averaging (much better than incoherent $|V|^2$)
  - Done: Tests by Schmitt *et al.* (2008) and Jorgensen (NMT)
  - TBD: Improve errors (e.g., “lucky” packets, filtering, de-dispersing)
- Imaging
  - Working: Import model data (ASCII) into CASA (Elias, Edel)
  - Working: Study using model data + realistic errors (Elias, Edel)
  - TBD: Test/Adapt imaging algorithms (e.g., polcal and MFS)

Instrumental Polarization





- Single-telescope IP (Elias *et al.* 2008)
  - NPOI (siderostats + feed system, no beam combiner)
  - Approximate mirror coatings
  - IP changes slowly versus time/pointing

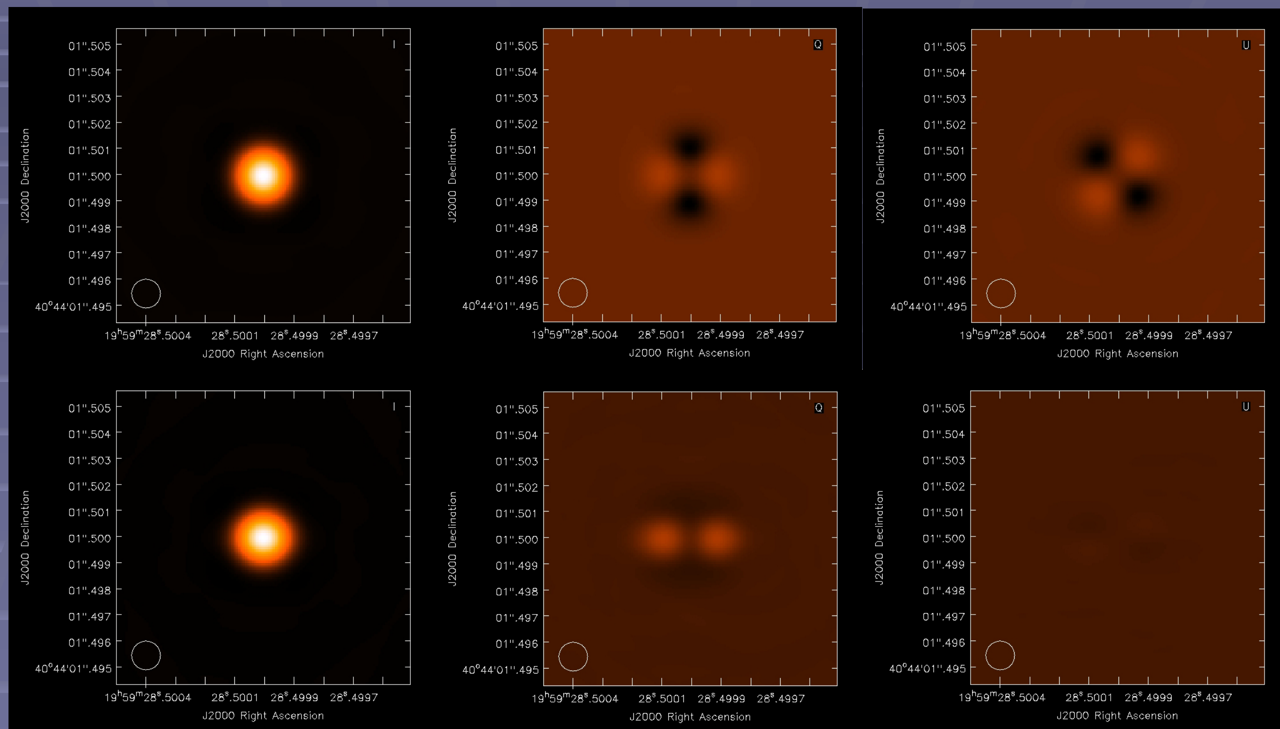
Simulation Parameters

- Be star simulations (UWO)
  - λ = 2.2 μm
  - Multiple inclinations
  - Multiple density models
  - Disk oriented such that integrated U = 0
- Elias and Edel imaging simulations with CASA
  - λ = 2.1-2.5 μm, 15 channels
    - 14 channels estimated, waiting for real data
  - V = 0 magnitude
    - B0V Be star ~ 61 pc distant
  - Nine 1.8m antennas, arranged in a "Y" configuration (MROI)
  - 1500m max baseline (long compared to MROI!)
    - Even 100m sees the disk in Q, though
    - Baselines ~ 3x smaller at visible wavelengths
  - Five second integrations
  - Poisson noise
  - Phase noise σ_{ϕ}~ 10 deg (Gaussian)
    - Eventually, we'll employ Kolmogorov statistics with raw data

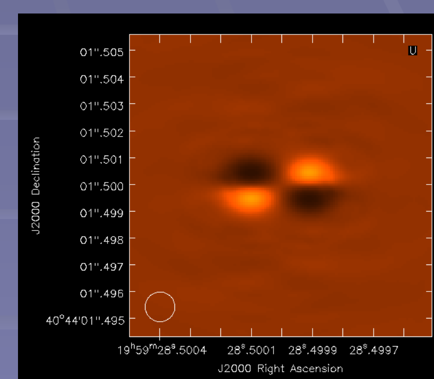
Simulation Images

i = 0 deg

i = 90 deg

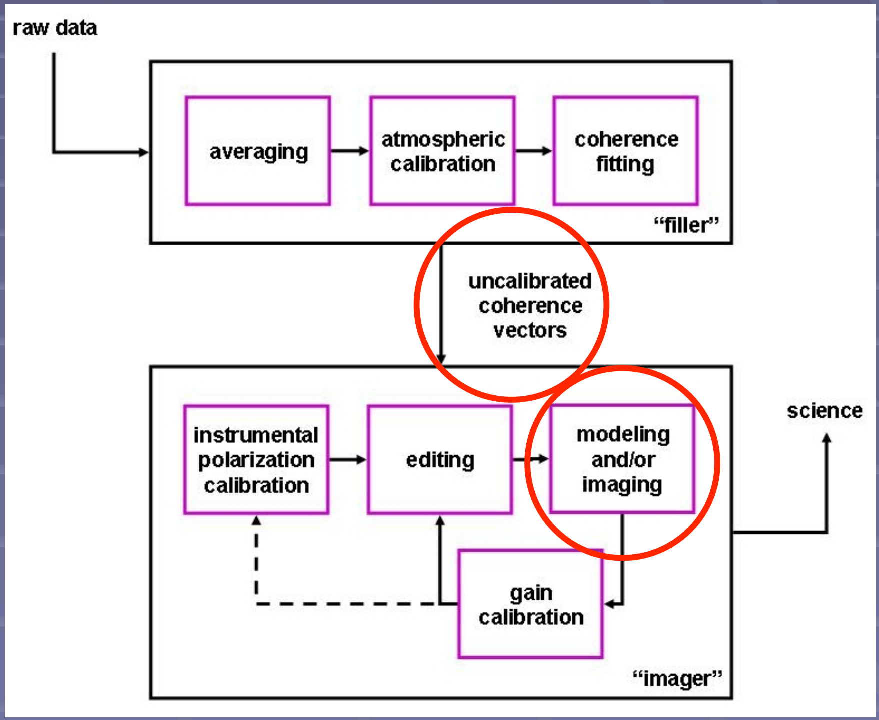


~ 1-2% polarization



Strawman E2E Data Reduction

- A "filler" must be written by each facility
  - Averaging and atmospheric calibration includes zero-spacing and correlation quantities
- Much of the "imager" functionality already exists in CASA, but OI-specific modifications may be required
  - polcal, MFS
  - Matrix transformations to obtain coherence vectors
- Red circles = Stas Edel's work



Conclusion

- OIP will be a powerful technique for this generation of instruments and especially the next
- I maintain an OIP web page with links to relevant journal articles, news, etc.
  - https://sites.google.com/site/astoptintpol/
  - Ask me to be listed as an “interested person”
- We plan to write a proposal (starting ~ 9/2011) to design, study, and create:
  - A full-Stokes OIP beam combiner
  - Full-Stokes OIP data-reduction algorithms

  → Details TBD

→Interested in participating? If so, feel free to contact me.

Epilogue

And now for something completely different:

- I work at NRAO in Socorro
- I've been writing EVLA proposals for Algols-like binaries
- If you have ideas for radio observations for the stars you're working on (single objects, small classes, large surveys), contact me!