Resolving the Structure of Disks Around Be Stars

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Rapidly rotating massive stars that eject gas into a circumstellar disk

Review: Porter & Rivinius 2003
• Properties of Be stars

• Interferometric observations of Be stars
  – Geometry and size of Be star disks
  – Multi-wavelength structure of the disks
  – Small scale asymmetries in the light distribution of the disk
  – Long-term campaign to monitor changes in the disk of Be stars
Evidence for Disks Around Be Stars: Infrared Excess

Touhami et al. 2010

Visible spectrum matches stellar spectral energy distribution
Evidence for Disks Around Be Stars: Infrared Excess

Visible spectrum matches stellar spectral energy distribution

Infrared excess above stellar spectrum

Touhami et al. 2010
Evidence for Disks Around Be Stars: Hα Emission Line Profiles

Gies et al. 2007
Evidence for Disks Around Be Stars: 
Ha Emission Line Profiles

Rotation of circumstellar disk

Gies et al. 2007
Time Variability of Hα Emission Lines

- V/R variations
- Variable on timescales of days to decades

Stefl et al. 2009
Time Variability of Hα Emission Lines

Stefl et al. 2009

Hanuschik et al. 1995

Density wave enhancement
Evidence for Disks Around Be Stars: Spatially Resolving the Disk with Long Baseline Interferometry

Quirrenbach et al. 1994
Mark III Interferometer

Baldwin & Haniff 2002
COAST Interferometer
Geometry of Be Star Disks
Measured using Interferometry
Geometric Models of Be Star Disks

- Zeta Tau observed in Hα emission at NPOI
- Elliptical Gaussian model
- Flattened disk inclined nearly edge-on
- Tycner et al. 2004
Physical Model: Isothermal Disk in Keplerian Rotation

- Geometry and density structure of the disk
- CHARA Classic K-band measurements
- Gies et al. 2007
Kinematic Model of Rotating Disk: High Spectral Resolution

- VLTI/AMBER Brγ emission
- Visibilities and differential phase
- Meilland et al. 2012
Kinematic Model of Rotating Disk: High Spectral Resolution

- VLTI/AMBER Brγ emission
- Kraus et al. 2012
Multi-Wavelength Sizes of Be Star Disks
How Does Disk Size Depend on Wavelength?

Touhami et al. 2011

$R(\text{disk}) / R(\text{star})$

WAVELENGTH (μm)

R$_d$/R$_*$

zeta Tau

Touhami et al. 2011
How Does Disk Size Depend on Wavelength?

\[ \frac{R_{\text{disk}}}{R_{\text{star}}} \]

CHARA/Classic (Gies et al. 2007)

CHARA/MIRC (Schaefer et al. 2010)

zeta Tau

Touhami et al. 2011
How Does Disk Size Depend on Wavelength?

Touhami et al. 2011
Multi-wavelength Disk Diameters

- Gam Cas
- PAVO - R
- MIRC - H
- Classic - K (Touhami)
Asymmetries in Be Star Disks
Time Variability of Hα Emission Lines

Stefl et al. 2009

Density wave enhancement

Hanuschik et al. 1995
- Asymmetry detected in differential phases
- Shift in position of bulge in disk
- GI2T - Vakili et al. 1998
Asymmetries in the Disk of Zeta Tau

- Asymmetry consistent with oscillation pattern created by one-armed spiral in disk
- Visibilities and differential phases - VLTI AMBER
Long-term Monitoring of Be Star Disks using the MIRC Beam Combiner at the CHARA Array
The CHARA Array
Mount Wilson Observatory

- 6 Telescopes
- Baselines ranging from 30 - 331 meters
Example uv coverage of Zeta Tau
MIRC Observations 2007-2009

- 2007Nov
  - S2E2W1W2
  - S1E1W1W2

- 2008Sep
  - S1E1W1W2

- 2008Dec
  - S1E1W1W2

- 2009Nov
  - S1E1W1W2
Elliptical shape and orientation of Zeta Tau disk
Asymmetry in the light distribution of Zeta Tau
• FWHM Major Axis ~ 1.8 mas
• On average, the central star contributes ~ 55% of the light in the H-band (41% in the K-band)
• Change in position angle of the major axis of 10-15°
• Motion of the asymmetry
Zeta Tau: Hα Profile Variability

Pollmann & Rivinius 2008
Zeta Tau: Hα Profile Variability

1995  2012  Period: 1428 days

E. Pollmann 2012
V/R Variation Continued Through Time Space of MIRC Observations

Schaefer et al. 2010
Mean position angle: -58.0° ± 1.4°
Semi-amplitude: 8.1° ± 1.7°
Maximum occurs at τ = 0.23 ± 0.03

Mean position angle from linear polarization: -58.1° ± 1.2°
(McDavid 1999; Stefl et al. 2009)
Tilt of disk associated with one-armed spiral density enhancement
Small Scale Asymmetries:
Shadowing of the Central Star
Gam Cas - Visibilities

Telescope Coverage

Visibilities

MIRC - H-band data from 2011 Sept 3
Gam Cas - Closure Phases

MIRC - H-band data from 2011 Sept 3
- Uniform circular disk star
- Elliptical Gaussian disk

Fix stellar diameter: 0.44 mas

Model Parameters:
- Disk major axis: 1.02 mas
- Disk minor axis: 0.76 mas
- Position angle: 204.3°
- 63% light from disk
- 37% light from star
Fit to Visibilities: Gam Cas
Small Scale Asymmetries in Light Distribution

- Uniform disk star
- Elliptical Gaussian disk
- Star partially shaded by disk
Can we measure the difference?

Bottom of star shaded by disk

Top of star shaded by disk
Visibilities

\[ \chi^2_v = 0.6 \]
Visibilities

$\chi^2 = 0.6$

$\chi^2 = 0.6$
Closure Phases

\[ \chi^2 = 20.4 \]
Closure Phases

$\chi^2 = 20.4$

$\chi^2 = 1.8$
Gam Cas - Closure Phases

MIRC - H-band data from 2011 Sept 3
Image Reconstructions of Be Star Disks
Image Reconstruction: Gam Cas

Geometric Model

MACIM Image
Image Reconstruction: Gam Cas

Geometric Model

MACIM Image

Reconstruct image while fitting for uniform disk star
MACIM + Model Fitting

- cd ~/Workshop/Software/macim
- Options for model fitting:
  - modelcode_ud.c
  - modelcode_im.c
- cp modelcode_ud.c modelcode.c
- make
- macim datafile.oifits -s 0.1 -w 50 -P p0 p1 -S s0 s1
  - p0, p1: % flux in UD disk, UD diameter
  - step sizes in flux and diameter (set to 0 to fix)
Image Reconstruction: Zeta Tau

Geometric Model

- Fit star as uniform disk
- Use elliptical Gaussian as prior to reconstruct disk

MACIM Image

Combined data set from 2007 to 2009
Challenges with Imaging Be Stars

- Goal: describe outward motion of gas and density enhancements through the disk over time
- Boundary between star and disk
  - model fitting: point source or uniform disk star
  - rapidly rotating central star?
- Overall shape and orientation of reconstructed disk is consistent with modeling
- Difficult to reconstruct small asymmetries in diffuse disk emission reliably
  - need good uv-coverage
  - include gaussian prior?
  - regularizer?
The End
Disks of Be stars may develop a spiral density wave that precesses prograde with the disk rotation.

Theoretical work by Ogilvie (2008) and Oktariani & Okazaki (2009) suggest that there is significant vertical motion associated with the spiral arm that might assume the form of a tilted disk. If so, perhaps this tilt precesses with the one-armed oscillation mode.

Martin et al. (2011) - transitions between shell and Be stars may suggest a warped, precessing disk. Torque from binary companion may cause oscillations in disk mass and inclination.

Previous evidence for precession in Be star disks
- Hummel 1998 (Gam Cas, 59 Cyg) - emission line widths
- Hirata 2007 (Pleione) - intrinsic polarization, Hα emission
What About the Polarization angle?

- Intrinsic polarization angle has remained remarkably stable over the last decade (McDavid 1999; Stefl et al. 2009)
- No evidence of changes as large as those seen in the interferometric data

Is There a Resolution?

- Polarization probes scattering radiation from the innermost part of the disk where it is probably co-aligned with stellar equator (source of ejected material)
- Tilt associated with larger scale structure of spiral oscillation in disk – measured by interferometry
Michigan Infrared Combiner: MIRC

- Designed for imaging
  - Combines light from 6 telescopes simultaneously
  - 15 visibilities and 20 closure phases
- 8 spectral channels across the H-band ($\lambda = 1.6 \, \mu m$)

Monnier et al. 2004, 2006
Stellar Diameter = 0.527 mas

Agrees with SED diameter of 0.52 mas (Y. Touhami)
Disk Contribution?
- Fix position angle and axis ratio based on infrared models
- Star diameter: 0.52 mas
- Disk FWHM: 0.84 mas
- 37% of light from disk
- Degeneracy between star/disk size and flux
Gam Cas: Binary Companion

Astrometric orbit for phi Per with MIRC image of disk

J. Monnier