Science Results and Future Prospects for Optical/IR Interferometry

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Outline of Talk

- History of Optical Interferometry
- Specialized Techniques
- Stellar Science
- Extragalactic Science
- Facility-Class Ground-based Interferometers
- Conclusions

Brief History of Optical Interferometry

- 1868 – Concept first outlined by Fizeau
- 1890/1921 – Michelson developed mathematical framework and then observed at Mt. Wilson with Pease
  - Measured Alpha Ori’s diameter to be 47 mas
- 1946 – Ryle and Vonberg built first radio interferometer
- 1956 – Harbury Brown and Twiss developed first intensity interferometer (Narrabri Int. Inter.)
- 1970 – Invention of Speckle Interferometry - Labeyrie
- Townes developed maser and used a heterodyne mode interferometer at 10 microns at McMath Telescopes

Development of Optical/IR Interferometry

Techniques in Optical Interferometry

- Visibility Measurements
- Closure Phase
- Differential Phase
- Astrometry
- Nulling

Visibility – Two telescopes

- Two-telescope interferometer records intensity of fringe signal from a complicated “source”
- Detected interference pattern can be used to ascertain geometry of target, given some a priori knowledge of system
**Closure Phase**

- Used to retain relative phase information between (pairs of) telescopes
- Allows one to eliminate atmospheric effects over interferometer and remove these from the final ‘phase’ of the source

**Differential Phase**

- Technique to record the difference in photocenters (via phase information) of the light from a binary system by examining two different wavelengths
- Operates best at longer wavelengths, using high spectral resolution
- Employed at the Keck Interferometer to study “Hot Jupiter” systems

**Astrometry (i)**

- Technique by which motion of a star (tangentially) can be used to infer the presence of companions
- Anticipated motion of the Sun based on the presence of Jupiter and Saturn — on the order of a milliarcsecond over decades

**Astrometry (ii)**

- Dual star technique records relative phase information between the primary target (planetary candidate) and secondary star (uninteresting background object)
- Both targets must be within the isoplanatic patch of the site (30-60°)
- Used by both the Keck Interferometer and the VLT Interferometer

**Nulling (i)**

- Motivated by desire to search for extrasolar planets
- Contrast ratio is more favorable at longer wavelengths \((10^6 \text{ vs } 10^{10})\)
- More easily detect exozodiastellar dust at these wavelengths — 1 zodi is 100 times intensity of Jupiter’s signature

**Nulling (ii)**

- Concept is to combine \(E\) vectors 180° out of phase at optical path difference zero
- Null depth is ratio of transmitted powers
- Stellar light is “nulled” while signature of planet may constructively interfere, depending upon fringe spacing
- Used by Keck Interferometer and LBT
Stellar Science – Single star angular diameters

• All stellar types now accessible:
  ▪ In the case of low-mass stars:
  ▪ Combine data with parallaxes to infer physical sizes.
  ▪ Currently restricted by lack of sensitivity and resolution.
  ▪ Goal is to probe lower-mass (smaller radius) systems.
  ▪ Higher spectral resolution will allow testing of both evolutionary & atmospheric models.
  ▪ No other direct way to determine diameters.

Stellar Science – Stellar population studies

• Combination of Hipparcos data and detailed color information
• 4902 stars with distances now known to 5% accuracy
• Allows detailed calculations of isochrones for nearby stars

Stellar Science – Pulsation

• PTI measurements of Zeta Dic using RV data and B-W method to get independent distance determination accurate to 1%
• Lack of ITI RV and detailed atmospheric knowledge of Cepheids hampers further progress
• Demonstrates differential pulsation of various atmospheric layers
• Correlates well with theoretical predictions of acoustic shock waves

Stellar Science – Binary Stars

• Fundamental parameters – R, M, L
  ▪ omi Leo orbit determined to 100 microarcsecond accuracy
  ▪ Used with m/s RV to find orbital inclination
  ▪ Mass to 0.5%; distance to 0.25%; Level of precision needed to fully test theoretical models

Stellar Science – Mass-loss/Mass-transfer

• Direct detection of asymmetric dust formation zone in WR 104.
• Scale of spiral is 100 mas, ~160 AU.
• Not predicted by theorists – NIR image is key to understanding mass-transfer process
  ▪ Mass-loss from carbon star IRC+10216
  ▪ Shown to be highly non-spherical and irregularly episodic
  ▪ Evidence for optically thick dust lane at 130° corresponding to 20° polarization signatures seen at other telescopes

Stellar Science – Young Stellar Objects (YSOs)

• One of key questions is to determine role of accretion disk in YSOs
• Imaging done of LkHa 101 at NIR – inner disk radius 7 AU (21 mas)
• Statistical samples indicate all measured sizes are too large compared to classical disk models
• Requires revisions including optically thin disk cavity and large grain sizes
Stellar Science – Stellar Spots

- Using aperture masking at VLT and observations with COAST able to show evidence for stellar spots on α Ori
- Observations show 3 bright spots at TiO wavelengths but not other wavelengths
- Direct probe of convective structure and mass-loss

Stellar Science – Stellar Disks

- COAST map of Be stellar disk around Zeta Tau
- Key diagnostic is distribution of emission line gas.
- Constrains geometric thicknesses, radial brightness profiles and opening angles directly.
- Spectrally resolved data get physical conditions & kinematics.
- Interferometric data have major implications for disk stability, wind-disk coupling, and disk collimation.

Stellar Science – Stellar Rotation

- PTI measurement of ellipticity of Altair
- Allows direct measurement of $\sin i$ and axis of rotation.
- Augments line-profile and radial velocity approaches.
- Direct challenge to models.

Extragalactic Science – Two new results!

- KI NIR observations of NGC 4151 (Seyfert 1)
- Measured high-visibility components which implies a compact source of emission ($<1.52$ mas at 3 sigma)
- Rules out emission mechanism requiring radius $> 0.05$ pc from the black hole

Extragalactic Science (ii)

- VLT NIR observations of NGC 1068 (Seyfert 2)
- Measured visibility implies both compact ($<5$ mas) and large component ($40+\text{ mas}$) contributing to the flux
- Only a portion of the measured flux is from scales $< 0.4 \text{ pc}$

Nota Bene

- All stellar science shown was with “testbed” interferometers
  - Small apertures
  - Limited functionality
  - Technology prototypes
- New class of optical/IR interferometers coming online
  - Facility class instruments – large apertures/dedicated observing staff
  - Specific functionality – multiple instrument suites
  - Mature technology
**Ground-based Interferometers**

- **Keck Interferometer**
  - 2 Kecks + 4 Outriggers
  - NIR-MIR
  - Funded by NASA, CARA
  - Keck Foundation
  - Built by JPL
  - First fringes in 2001
  - Missions related to NASA

- **Origins**
  - Astrometry
  - Nulling
  - Differential Phase
  - Imaging

- **VLTI**
  - 4 UT and 4 AT
  - NIR-MIR
  - Funded and built by ESO members
  - First fringes in 2001
  - Primary missions:
    - Astrometry
    - Imaging

- **CHARA**
  - 6 telescopes
  - Optical - NIR
  - Funded and built by GSU/NSF and private foundations
  - First fringes 1999
  - Primary mission:
    - Study of binary stellar systems

- **MROI**
  - 10 telescopes
  - Optical-NIR
  - Y-configuration
  - Relocatable – 34 pads
  - Funded by US Gov
  - Built by NMT and Cavendish Lab Univ. of Cambridge

**MROI Science Mission (i)**

- Stellar Science goals:
  - Mass loss in single stars:
    - Convection: latitudinal or longitudinal?
    - Distribution of circumstellar material, the玉米
    - Impact of latarity, shocks and wind geometries.
  - Mass-loss in binaries:
    - Recurrent novae & symbiotics. Orbit, wind & accretion geometry.
    - Eclipsing binaries. Clumpness in mass transfer.
  - Dynamical studies:
    - Pulsational models for Cepheids, Mira, RV Tauri etc.

**MROI Science Mission (ii)**

- YSO and Planetary Science goals:
  - Protostellar accretion:
    - Imaging of thermal dust and scattered emission on sub-AU scales.
    - Disk clearing as evidence for the epoch of planet formation.
    - Emission-line imaging of jets, outflows and magnetically channelled accretion, x-winds.
  - Companions:
    - Physical and compositional characterization.
    - Direct detection of sub-stellar companions to M dwarfs.
MROI Science Mission (iii)

- AGN Science Goals:
  - Verification of the unified model
  - Direct detection of the obscuring tori
  - Geometry and orientation of the tori – thick, thin or warped? Relationship to other observables
  - Nature and contribution of nuclear and extra-nuclear starbursts
  - Imaging and dynamics of the BLR in nearby AGN
  - Detection of optical and infrared counterparts of synchrotron jets

Why will MROI work?

- Large number of telescopes => good UV coverage
- Large number of telescopes => large numbers of closure phases
- Movable telescopes => Ability to image very large range of spatial scales
- Extremely high throughput (20%) => Extragalactic capability
- Optimized transport and correlator => Minimal losses of visibility
- Draws on best technological features of all interferometric arrays to date

Space-based Missions

- SIM
  - NASA astrometry project
  - Main missions are astrometry related science of planet detection, stellar and extragalactic astronomy
  - Launch in 2010

- TPF/Darwin
  - Joint projects of NASA and ESA
  - Main missions are to find extrasolar planets using either nulling or coronography
  - Launch in 2015-2020 window

Conclusions

- Optical/Infrared Interferometry is now technically mature
- Tremendous advances in our understanding of galactic astrophysics will be made as more facility-class interferometers become available
- Optical/Infrared interferometers are NOT limited to galactic sources – this will become more evident as imaging arrays and large apertures are regularly employed

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