Long Baseline Optical Interferometry
and the Search for Exo-Planets

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Stellar Interferometry

- What is it, why do it?
  - Introduction to Stellar Interferometry
- The search for planets outside our solar system
  - Historical perspective, discoveries in the last ~4 years
- Interferometry and Planets
  - Major approaches for exo-planet detection
- Projects and Missions, technologies under development
  - *Keck Interferometer*
  - *Space Interferometry Mission*
  - Space Technology 3
  - Terrestrial Planet Finder (TPF)
What is an Optical Interferometer?

- An interferometer combines the light from several small telescopes to yield the angular resolution of a much larger telescope.
Ground Optical Interferometers

Navy Prototype Optical Interferometer
460m baseline

Sydney University 600m

Palomar Interferometer
110 m
Why Interferometry?

1 - Imaging resolution
   \( \lambda/B \) for an interferometer vs. \( \lambda/D \) for a telescope
   \( B \), separation of apertures, can cost-effectively be made very large

2 - Astrometric Accuracy
   Interferometers have a simple geometry which can be accurately monitored to minimize systematic errors
   Interferometers use starlight efficiently

3 - Nulling, interferometers have the ability to "null starlight" with extreme precision, in order to see the presence of planets or other dim objects orbiting a star
What does a stellar interferometer do?

The peak of the interference pattern occurs when the internal path delay equals the external path delay.

Interference fringes are detected when $x \sim 0$ within $\sim \lambda$

$\lambda$ mm~cm (radio)

$\lambda$ $\sim \mu$m optical
About Fringes

Narrowband (laser) fringe \( \Delta \lambda \sim 0 \)
- Fringes at all delays

1 wavelength

Wideband (white light) fringe \( \Delta \lambda \gg 0 \)
- Number of fringes \( \sim \frac{\Delta \lambda}{\lambda} \)
- There is a well defined central fringe

- Fringe position tells us about position of source
- Fringe visibility tells us about structure of source
  (extended sources have reduced fringe visibility)
Requirements on Fringe Stabilization

Vibrations blur out the fringe

10 nm rms

Fringe Visibility (contrast)

50 nm rms

Fringe Position (or phase)

200 nm rms

Need real-time control of pathlength to ~10 nm (\(\lambda/50\)) for high fringe visibility
Imaging with an Interferometer

- The interferometer measures the Fourier transform of the object.
- Each baseline orientation selects one point in the (u,v) plane.
  - The data for this point is the fringe visibility and phase.
- With many baseline orientations, you fill in the (u,v) plane.
- The image is reconstructed from these Fourier-domain measurements.
Astrometry, the Position/Motion of Stars

Laser gauge measures internal delay
(adjusted by delay line, sensed by fringe detector)

External path delay
\[ x = B \cos(\theta) \]

telescope 1  optical fiducial  optical fiducial  telescope 2

detector  beam combiner  laser

Laser path retraces starlight path from combiner to telescopes
Astrometric Accuracy

- Traditional astronomical telescopes can measure the position of a star relative to nearby background stars ~1 milliarcsec (mas)
- The next generation of Stellar interferometers hope to improve on that by 10, 100 and eventually a factor of ~1000
Search for Planets Orbiting Other Stars

- Humans have been curious about the possibility of planets around other stars for hundreds of years.
- In the middle of the 20th century, the favored technique was astrometry, looking for the sideways wobble of a star due to the gravitational pull of the planet.
- At that time, astronomers using photographic techniques thought they had found a Jupiter-sized planet around Barnard’s star. This discovery turned out to be false.
- It wasn’t until 1996 that a real planet was discovered, and not by astrometry.
51 Peg, the First Extra-Solar Planet

- Discovered by Michel Mayor and Didier Queloz, Oct 1996, confirmed by G. Marcy and P. Butler
  - mass > 0.44 Jupiter
  - Period 4.2 days
  - Distance from star 0.051 AU
- Since then the doppler technique has discovered ~35 planets around nearby stars.
- These planets are very different the ones in our own solar system
Known Planets around Nearby Stars

Planets found using radial velocity techniques

Orbital Semimajor Axis (AU)

Upsilon Andromedae
Properties of Known Planets

- ~Jupiter mass objects
- Many in close (<0.2AU) orbits around the parent star
- Eccentric Orbits (elliptical, not circular orbits)
- What are the properties of planets in our solar system?
  - Jupiter mass Gas Giants far from the Sun (5~40 AU)
  - Rocky planets (Earth, Mars, Venus, Mercury) near the Sun
  - Circular, coplanar orbits
- What happened to Astrometric detection of planets?
Interferometry and Planet Detection

- There are several techniques for detecting planets around nearby stars.
  - Indirect - Doppler/radial velocity of the star
    - High resolution spectrographs on large telescopes
  - Indirect - Astrometry (transverse wobble) of the star
    - Long baseline interferometer on the ground and in space
  - Direct - IR, look for the IR emission of the planet
    - "hot jupiters" from large ground based interferometers
    - Earths with large cryogenic interferometers in space
The Next 2~12 Years

- Keck Interferometer
  - Astrometric Planet detection \( \sim 20 \)uas
  - Hot Jupiter direct detection
  - Dust around nearby stars
- Space Interferometer Mission SIM
  - Astrometry \( \sim 1 \)uas (\( \sim 3 \) Earthmass)
  - Demonstrate Nulling in space
- Terrestrial Planet Finder TPF
  - Direct detection of Earth-like planets
  - Low resolution spectra of atmosphere
Keck Interferometer

Keck Observatory (Caltech/U.C.)
Twin 10m telescopes on Mauna Kea

Keck Interferometer is an addition to the Observatory that adds 4 1.8m "outrigger" and a beam combining facility so that all 6 elements of the array can operate as a single Telescope ~100 m across.
Palomar Testbed Interferometer
Technology Prototype for Keck Interferometer

110 m baseline 1.6-2.4um
Direct Detection of Hot Jupiters

Phase Difference Interferometry for Planet Detection
Direct Detection of Hot Jupiters

- Problem is not SNR - need to control systematic errors
- Use two-color phase referencing
  - Use object observed at a short wavelength as phase reference
    - Center of light will be close to star
  - Observe object at a longer wavelength for science measurement
    - Center of light will be displaced toward planet
  - Phase difference is observable
    - Very insensitive to systematics
- Observations of GL229B showed that significant changes in the flux ratio may be present just within the 1.6 and 2.2 um bands.
Exo-Zodi

- NASA is very interested in finding Earth like planets around nearby stars.
- There is one unavoidable source of astrophysical "noise", the disk of dust around the target star.
- For our own solar system, the dust in the inner solar system will emit more 10um radiation than an Earth (~50).
- To properly plan the TPF mission NASA needs to survey a number of nearby stars for the level of exo-zodi dust.
Nulling Interferometers

- rooftop b
- mb
- bs
- comp
- ma
- output
- green ray = beam#1
- input
- red ray = beam#2

Laser Diode OPD Scan

Sample Number

Null Depth

Relative Intensity

Sample Number
Basement Keck Interferometer
Component Hardware

Fast delay lines

Dewar and camera

Laser metrology
K1 Adaptive Optics
Outrigger 1.8m Telescopes
Space Interferometry Mission (SIM)
SIM An Astrometric Mission
to Measure Positions of Stars with Extreme Accuracy

ExoPlanet Detection
Cosmic Distance Scale
Galactic rotation, Dark Matter

Demonstrate Starlight Nulling
with sub-nanometer stability
(for TPF mission)
Demonstrate synthetic aperture imaging

SIM extends the catalog
both in astrometric accuracy
and in star magnitude (faintness)
A Sense of Scale
Astrometric Planet Detection

1 A.U. ~ 150,000,000 km

~400 stars in the solar neighborhood within 10 parsec
2 million A.U., 3 x 10^{14} km

Nearest Stars: ~1.3 parsec
280,000 A.U.
42 trillion km

Sun's reflex motion (Jupiter) ~ 750,000 km
Sun's motion from the Earth ~ 500 km
Astrometric Planet Detection

Planetary systems inducing only low radial velocities ($\lesssim 3 \text{m/s}$) in their central star that can't possible to detect from the ground can be detected through the astrometric displacement of the parent star.

Detection Limits
SIM: 1 µas over 5 years (mission lifetime)
Keck Interferometer: 20 µas over 10 years
Technical Challenges

- Making a large (~12 meter) light weight/flimsy structure in space stable at the nanometer level (nano-technologies)
- Measuring the positions of the optical elements on SIM, with picometer accuracy to enable astrometry (positions of stars) at the ~1 uas (5 picoradian) level. (pico-technologies)
  - Detect a 2mm motion on the Moon, from Earth.
  - Goal is to detect the wobble of a ~3 earth mass planet around a star 10pc (30 lightyears) away.
Flexible truss ~5 Hz resonance
Simulated spacecraft disturbance (reaction wheels)
Active isolation of disturbance & active optical loop
(using laser interferometry as the sensor)
SIM System Testbed (STB-3)

Now: 3 baselines on optical table
- Three interferometers now functioning on an optical table
- Completed detailed design of SIM-scale flexible structure to be built and installed by end-2000

Soon: 3 baselines on structure
- Begin nanometer active control experiments on flexible structure
- Three baselines, full scale
Picometer measurement technology

Component technologies
superprecise optical elements
picometer laser gauges
freq stabilized lasers

Microarcsec Metrology Testbed
fully functional interferometer
tested in vacuum at picometer
levels
verify testing procedure for
flight hardware
Terrestrial Planet Finder (TPF)

Direct Detection of Earth-like planets around nearby stars
Interferometric starlight nulling by $\sim 10^6$ to detect 10um (IR) light from the planet
$\sim 10$ hrs of observation to detect an Earthlike planet @ 10pc
2~4 weeks to measure a low resolution spectra of the atmosphere, to identify $\text{H}_2\text{O}$, CO2, O3

$\sim 4$ large collecting apertures $\sim 3$m dia
Cryo optics ($< 50$K)
Separated spacecraft interferometry 50~500m
Pathlength control (nulling $\sim 1$nm)
Multiple Spacecraft Interferometry
ST-3 Technology Mission

- The New Millenium Program ST-3 Mission will provide validation of key enabling technologies for TPF when it flys in late 2003 including:
  - Separated S/C interferometry
  - Precision formation flying
  - Real-time optical control of a separated S/C interferometer
  - Angular and linear metrology
  - Inertial referencing for phasing and guiding
  - Separated S/C interferometer I&T techniques
Earth's Around Other Stars?

Near term goals
   Keck Interf  Uranus/Neptue mass (outer planets)
   SIM  Terrestrial Planets ~1 AU (few Earth masses)

Longer term goals
   TPF IR detection of Earths, H2O, CO2, Oxygen
   Detailed atmospheric studies of exo-Earth
   (eventually images of oceans/continents)
Keck Interferometer Status