Webster Cash
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X-ray Interferometry
Collaborators

• Ann Shipley, Karen Doty, Randy McEntaffer, & Steve Osterman at CU
• Nick White – Goddard
• Marshall Joy – Marshall
• David Windt and Steve Kahn - Columbia
• Mark Schattenburg - MIT
• Dennis Gallagher – Ball Aerospace
X-ray Telescopes

X-ray telescopes are sensitive to material at millions of degrees.
Capella 0.01"

Capella - 10 milliarcsec resolution - .01 sq.cm
Capella 0.001”

Capella - 1 milliarcsec resolution - 0.1 sq.cm
Capella 0.0001"
Capella 0.00001"

Capella - 10 microarcsec resolution - 100 sq.cm
Capella 0.000001”

Capella - 1 microarcsec resolution - 10000 sq.cm
AR Lac
Simulation @ 100μas
AGN Accretion Disk Simulations @ 0.1 μas

C. Reynolds, U. Colorado

M. Calvani, U. Padua
Need Resolution and Signal

If we are going to do this, we need to support two basic capabilities:

• Signal
• Resolution
X-ray Sources Are Super Bright

Example: Mass Transfer Binary
10^{37}\text{ergs/s} from 10^9\text{cm} object

That is \sim 10,000L_\odot from 10^{-4}A_\odot = 10^8 B_\odot
where \(B_\odot\) is the solar brightness in \text{ergs/cm}^2\text{s/steradian}

Brightness is a conserved quantity and is the measure of visibility for a resolved object

Note: Optically thin x-ray sources can have very low brightness and are inappropriate targets for interferometry.
Same is true in all parts of spectrum!
Minimum Resolution

![Graph showing the relationship between resolution limit, baseline, source temperature, and frequency.](graph.png)
Status of X-ray Optics

• Modest Resolution
  – 0.5 arcsec telescopes
  – 0.5 micron microscopes

• Severe Scatter Problem
  – Mid-Frequency Ripple

• Extreme Cost
  – Millions of Dollars Each
  – Years to Fabricate

Need Easier Approach
Classes of X-ray Interferometers

Dispersive
Elements are Crystals or Gratings

Non-Dispersive
Elements are Mirrors & Telescopes
Achieving High Resolution

Use Interferometry to Bypass Diffraction Limit

Michelson Stellar Interferometer

\[ R = \frac{\lambda}{20000D} \]

- \( R \) in Arcsec
- \( \lambda \) in Angstroms
- \( D \) in Meters
Creating Fringes

Requirements

• Path Lengths Nearly Equal
• Plate Scale Matched to Detector Pixels
• Adequate Stability
• Adequate Pointing
• Diffraction Limited Optics
Pathlength Tolerance Analysis at Grazing Incidence

$B_1 = \frac{\delta}{\sin \theta}$

$B_2 = B_1 \cos(2\theta)$

$OPD = B_1 - B_2 = \frac{\delta [1 - \cos(2\theta)]}{\sin \theta} = 2\delta \sin \theta$

If OPD to be $< \lambda/10$ then $\delta < \frac{\lambda}{20 \sin \theta}$

$d(Baseline) < \frac{\lambda}{20 \sin \theta \cos \theta}$

$d(focal) < \frac{\lambda}{20 \sin^2 \theta}$
A Simple X-ray Interferometer

Flats

Beams Cross

Detector
Wavefront Interference

\[ \lambda = \theta s \quad \text{(where s is fringe spacing)} \]

\[ s = \frac{L \lambda}{d} \]
Optics

Each Mirror Was Adjustable
From Outside Vacuum
System was covered by thermal shroud
Stray Light Facility MSFC

Source, filter and slit

Interferometer

CCD

16m

100m

Used Long Distance To
Maximize Fringe Spacing
CCD Image @ 1.25keV

2 Beams Separate

2 Beams Superimposed
Fringes at 1.25keV

Profile Across Illuminated Region
Test Chamber at CU

Ten Meter Long Vacuum Chamber for Testing

Came on-line early May

EUV results good
Upgrade to x-ray next
Actual Image at 30.4nm

Image of Slit
Reconstructed from 4 azimuths
MAXIM

The Micro Arcsecond X-ray Imaging Mission

Webster Cash    Colorado
Nicholas White  Goddard
Marshall Joy    Marshall

PLUS Contributions from the Maxim Team

http://maxim.gsfc.nasa.gov
Maxim:
A Few Science Goals

Goal

Resolve the winds of OB stars:
Resolve pre-main sequence stars:
Image center of Milky Way:
Detailed images of LMC, SMC, M31:
Image jets, outflows and BLR from AGN:
Detailed view of starbursts:
Map center of cooling flows in clusters:
Detailed maps of clusters at high redshift:
Image Event Horizons in AGNS:

What kind of shocks drive the x ray emission?
How does coronal activity interact with disk?
Detect and resolve accretion disk?
Supernova morphology and star formation in other settings
Follow jet structure, search for scattered emission from BLR
Resolve supernovae and outflows
Resolve star formation regions?
Cluster evolution, cooling flows

Probe Extreme Gravity Limit
Flats Held in Phase
Sample Many Frequencies
As More Flats Are Used
Pattern Approaches Image
rces in the same

e source that is
dispaced to the lower left. The image on the right shows 9000 total events for

ity of the higher

energy source. Even though the higher energy source is in the first maxima of

the other, the two can still be easily distinguished.
Clockwise from upper left: Probability distribution; 100 photons randomly plotted; 9000 photons; and 5000 photons.
continuum and the contribution of photons with energies between 5-6 keV to ion of the
These figures show the probability distribution for the 1keV portion of the continuum and the contribution of photons with energies between 0-1keV to the data simulation.
The probability distribution on the left represents a continuum of energies between 1keV and 6keV. In the right figure, 16000 random events were recorded according to this distribution.
Stars

Simulation with Interferometer

Sun with SOHO
3C273 with Chandra

Simulation with Interferometer
Four Difficult Areas

• **Fabrication of Interferometer**

• **Internal Metrology**
  – Hold Mirrors Flat and In Position

• **Formation Flying**
  – Hold Detector Craft in Position

• **Pointing**
  – Hold Interferometer on Target
Maxim

"The Black Hole Imager"

Capella - 1 microarcsec resolution - 10000 sq.cm

0.1 μ
10,000cm² Effective Area
0.4 - 7.0 keV
Maxim Pathfinder

100μas Resolution
100cm² Effective Area
0.4-2.0keV + 6keV

Two Spacecraft
Formation Flying at
450km Separation
### Optics Spacecraft

- **Carries:**
  - Finder X ray Telescopes
  - Laser Ranging System

- **Size:** 2.5x2.5x10m
- **Pitch&Yaw Stability:** $3 \times 10^4$ arcsec
- **Pitch&Yaw Knowledge:** $3 \times 10^{-5}$ arcsec
- **Roll Stability:** 20 arcsec
- **Position Stability:** ----

### Detector Spacecraft

- **Carries:**
  - X-ray Detector Array
  - Laser Retro Reflectors
  - Precision Thrusters

- **Size:** 1x1x1m
- **Pitch&Yaw Stability:** 20 arcsec
- **Roll Stability:** 20 arcsec
- **Lateral Stability:** 5mm
- **Lateral Knowledge:** 50 microns
- **Focal Stability:** 10 meters

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**Maxim Pathfinder Mission Concept**

![Diagram of the Maxim Pathfinder Mission Concept](image-url)
Optics Craft
Front View

Prime Interferometer

Yaw Sensor
Consider, instead, line F.
Mount the visible light interferometer on structures at the ends of line F. They then maintain 1nm precision wrt to guide star that lies perpendicular to F. This defines pointing AND maintains lateral position of convergers.
(40pm not needed in D and E after all.)
A, B, C, D and E all maintain position relative to F.
Detector

- Energy Resolution Necessary for Fringe Inversion
- CCD is inadequate
- To get large field of view use imaging quantum calorimeter
Metrology

**Tightest Tolerance is Separation of Entrance Apertures**

\[
d = \frac{\lambda}{20\theta}
\]

for tenth fringe stability

At 1keV and 2deg, \(d=1.7\text{nm}\)
At 6keV and 0.5deg, \(d=1.1\text{nm}\)

Requires active thermal control and internal alignment
Laser Beam
Split and Collimated

Laser
Collimator
Collimated Beams Cross at 450km
Optics Craft
450km to Detector Craft
**Detection of Pattern**

Fringes have 14cm period at 450km
Need stability and information wrt to the celestial sphere at level of required resolution.

L2 or Fly-away orbit probably necessary

Baseline design calls for two stellar interferometers. One each for pitch and yaw. SIM class interferometers more than adequate.
Delta IV (H) 5m diameter x 19.8m long

Launch Fairing Removed

Payload

Spacecraft

Baffling

Detector Spacecraft (2.2m)

Optics Instruments (10m)

Optic Spacecraft Systems (2.2m)

LAUNCH CONFIGURATION
ORBIT CONFIGURATION

Detector Spacecraft

Solar Array
(7 m^2, projected area)

Optic Spacecraft
Stowed Orbit Payload Spacecraft Subsystems are mounted in this volume

DETECTOR SPACECRAFT

Payload

Stowed

Spacecraft

Spacecraft Subsystems

Fixed Solar Array
(6m^2 shown)

this volume
Maxim Design
Full Maxim
Maxim Limitations

• If primary flats are on separate spacecraft, they can be flown farther apart. Resolution increases.

• Limited by visible light aspect from stars
  – They’re all resolved at 30 nano-arcsec!
    • Find non-thermal visible sources
    • Use x-ray interferometry for aspect too.

• Solve aspect problem and reach $10^{-9}$ arcsec
Integrated System Modeling

Ball Aerospace Technologies Corporation

M. Lieber
D. Gallagher

Will lead to single most important tool in development and definition of x-ray interferometry
Integrated End-to-End Modeling Environment

- Integrated modeling seamlessly combines the subsystem models from well-established software tools.
- Allows one to rapidly study parameter interaction of disparate variables from different disciplines. Integrated models facilitate GUI development - multi-user system tool.
- Standard interfaces minimize errors and miscommunications between disciplines.
Example of MAXIM Pathfinder

- Structures, optics, controls, signal processing, disturbances
Optical Toolbox: Key Element of Optical Performance Modeling

- Geometric ray trace
- Diffraction analysis (PSF outputs)
- Easy introduction of mirror distortions from thermal or vibration
- Optics tied to NASTRAN structural model
- Active control modeling of metrology system and active optics
- Interfaces with imaging and detection modules
MAXIM Pathfinder PSFs with Different Number of Optical Elements

2 segments

4 segments

32 segments

PSF  Image  Log image
MAXIM Physical Model

MAXIM Integrated Model

Celestial objects

Converger and Delay Line S/C

Collectors & Hub S/C

Command and Control

Detector S/C
MAXIM System Modeling Leveraged From NASA and Other Programs

- GSFC - Expertise and models for formation flying - FF lab
- Optical metrology - Ball/GSFC Cross Enterprise contract, Ball/JPL Starlight program
- Integrated modeling environment and MATLAB/Simulink toolset - NGST, TPF, VLT
- Wavefront control - see next slide
Example Wavefront Control Modeling - Initial Phase Map of NGST

- Wavefront control tools from NGST program and extensive work on phase retrieval by JPL.

- RMS random segments = primary [1e-4 1e-4 4e-5 1e-5 1e-4 0]

- Secondary = offsets

Random errors for 36 segments

- [x-decenter y-decenter piston tip tilt clocking]
Status: X-ray Interferometry in NASA Planning

Structure and Evolution of the Universe (SEU) Roadmap
Maxim Pathfinder Appears as Mid-Term Mission Candidate Mission for 2008-2013
Maxim Appears as Vision Mission Candidate Mission for >2014

McKee-Taylor Report
National Academy Decadal Review of Astronomy
Released May 19, 2000
Prominently Recommends Technology Development Money for X-ray Interferometry
“X-ray Roadmap” to Image a Black Hole

**Imaging**

- Chandra
  - ROSAT Einstein
  - 100-1000 cm²
  - 0.5 arc sec

- Constellation-X
  - ASCA RXTE
  - 3 m²
  - Indirect imaging via spectroscopy

**Spectroscopy**

- XMM Astro-E
- Indirect imaging via spectroscopy

**Optimize MAXIM Parameters**

- MAXIM Pathfinder
  - 100 cm²
  - 2 m baseline
  - 100 µarc sec

**1000 times finer imaging**

- MAXIM
  - 1000 cm²
  - 100-1000 m baseline
  - 100 nas

**Million times finer imaging**

**Do they exist?**

- 2000

**Where are they?**

- 2008

**Conditions in the inner disk**

- 2014

**X-ray Interferometry Demonstration**

- 2020

**Black hole Imager!**

- Spectrally Resolved
Plan

- Technology Development
  - Start with NIAC and SR&T Funding
  - Mission Specific Funding
- Maxim Pathfinder
  - New Start 2008
  - Develop & Test Technology for Maxim
- MAXIM
  - Five Years after Pathfinder
We have already found this black hole and will have these pictures before 2020.