Sub-arcsecond to μ-arcsecond Resolution X-ray Imaging of SMBH with a novel method MIXIM

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Angular Resolution is essential

Log(Angular Resolution [arcsec]) vs Log(Wavelength [m])

- D=0.1mm
- D=1m
- D=10m
- D=10km
- D=10000km
- Naked Eye
- Galileo
Wide Wave Length Band is also essential.

Angular Resolution is essential, again.
Grazing Incidence Mirror + X-ray CCD is the de facto standard of X-ray Observatories since ASCA (1993)

- Angular resolution is exceptionally good for Chandra, 0.5″.
- Better or similar resolution mirror is very difficult to make (cost etc).
- Satellites must be big when grazing incidence mirrors are employed.

Our challenge to this field consensus → MIXIM
Multi-Pinhole(Slit) Camera is the baseline

STACK these multiple images in the analysis

http://blog.goo.ne.jp/hanahana/haru04/e/a8ef27218dee3713136a89943109a431
Multi Image X-ray Interferometer/Imager

Hayashida+2016

Parallel Beam

Grating

Pitch $d$

Opening

Fraction $f$

Distance $z$

X-ray Pixel Detector (CCD/CMOS)

Stack

• Only employ a Grating and an X-ray Pixel Detector

• Image profile detected reflects the profile of the X-ray source.

• Stacking the image with a period of $d$ in the analysis, accurate source profile is obtained.

• Image Width $\theta = f d / z = 0.4'' \left( \frac{f}{0.2} \right) \left( \frac{d}{5 \mu m} \right) / \left( \frac{z}{50 cm} \right)$

Chandra Resolution with a 50cm size satellite?

But, diffraction blurs the image significantly.
But, but, **Talbot Effect** can be employed

- **Talbot Effect**
  - Parallel Light through a grating makes **Self Image** of the grating at periodic distances. (H.F.Talbot, 1836)
  - Explained with **Diffraction** and **Interference** (Rayleigh, 1881)
  - Hard X-ray Talbot Effect in experiment (P. Cloetens, 1997)

- **Talbot Distance**
  \[ z_T = m \frac{d^2}{\lambda} \]

For \( \lambda=0.1\text{nm} (12\text{keV}) \) X-rays and a \( d=5\mu\text{m} \) pitch grating, Talbot distance \( z_T \) of \( m=2 \) is 50cm
Multi Image X-ray Interferometer Module (or Method, Mission) = MIXIM

Hayashida+ 2016, 2018

- X-ray Grating with >a few µm pitch and X-ray Imaging Spectrometer

- Select X-ray Events of which energy is within specific band around the Talbot condition
  \[ z = m \frac{a^2}{\lambda} \]
  - Band-pass of about 10% (for m=2; 20% for m=1) can be utilized. Wider than Si-detector energy resolution of 2~3%. Good for X-ray CCD and X-ray CMOS.

- Stacked Image tell us the X-ray source profile

c.f. X-ray Talbot (-Lau) Interferometer Momose+ (2003), Pfeiffer+ (2006) for Phase Contrast X-ray Imaging of Light Material

Figure from http://rsif.royalsocietypublishing.org/content/7/53/1665

Hoshino+ 2014 KONICA MINOLTA TECHNOLOGY REPORT Vol11
• X-ray Gratings of a few μm pitch are fabricated and purchased.
• Pixel size of the detectors should be a few μm or smaller, while X-ray CCDs pixel is 24μm or larger.
• Variety of CMOS pixel detectors designed for optical light.
• Some groups (Einstein Probe, FOXSI-3) succeeded in detecting X-rays with optical CMOS with 11μm pixel.
• We employed GSENSE5130 4.25μm pixel in 2017 and GMAX0505 2.5μm pixel in 2018, both from Gpixel Co.

Small pixel size enables us to detect X-ray polarization
See Asakura+ 2019, JATIS, 5(3) and Poster #501
Small Pixel → Photo-electron-Track → X-ray polarimetry

12.4keV

24.8keV

$r_H(\phi) = \frac{N_H(\phi)}{N_H(\phi) + N_V(\phi)}$

Asakura+2019
JATIS, 5(3)

MF =
7.63 ± 0.07% @ 12.4keV
15.5 ± 0.4% @ 24.8keV
SPring-8 BL20B2 200m beam line

2017 Nov, Dec, 2018 May, Jun (4.25μm) 2018 Oct, Dec (2.5μm)

Hayashida+2018 SPIE Proc.

d=4.8μm, f=0.2

d=9.6μm, f=0.2

Monochromatic Polarized X-ray Beam

Grating

CMOS

Optical Bench

Rotation Stage
d=9.6μm, f=0.2, z=92cm  Raw Frame Image 6s-exposure

Ex=12.4keV (m=1.0; meet Talbot condition)  Ex=10.0keV (m=1.24; NOT meet)

Following data were taken with exposure/frame of 0.1-1s with attenuator to prevent pileup
Event Extraction → Projection → Folding  \( \text{Ex}=12.4\text{keV} \)

Folded Profile

Visibility = \( \frac{\text{MAX} - \text{MIN}}{\text{MAX} + \text{MIN}} \)

* Two periods are plotted for display purpose

\( \text{d}=9.6\mu\text{m}, \text{z}=46\text{cm} \)

\( \text{Visib.}=0.59 \)

\( \theta=0.55'' \)

\( \text{d}=9.6\mu\text{m}, \text{z}=92\text{cm} \)

\( \text{Visib.}=0.88 \)

\( \theta=0.41'' \)

\( \text{d}=9.6\mu\text{m}, \text{z}=184\text{cm} \)

\( \text{Visib.}=0.78 \)

\( \theta=0.26'' \)
Energy Dependence of Visibility

E = 10.0 keV   E = 11.6 keV   E = 11.8 keV   E = 12.0 keV

E = 12.2 keV   E = 12.4 keV   E = 12.6 keV   E = 12.8 keV

E = 13.0 keV   E = 13.2 keV   E = 14.8 keV
Energy Dependence of Visibility → Band Width

d=9.6μm, f=0.2, z=92cm

10%

20%

Visibility

Single Pixel Event
H Double Pixel Event

Energy [keV]

m=2

m=1
1. Test large z case to obtain smaller (better) Image width <0.1”
2. First **2D imaging** by stacking two 1D gratings diagonally
   \[ z = 8.67 \text{m} \]
Resolution <0.1”, best ever achieved with X-ray astronomical imagers.

Synchrotron Source
150μm (0.15”) elongation along H-direction is suggested

Grating
d=9.6μm, f=0.2
CMOS
2.5μmpix

Projection

Ex=12.4keV

Visibility
=0.91
Period=0.23”
θ
=0.08”

H-Source Size>
Period

1pixel=2.5um

Grating
d=9.6μm, f=0.2
CMOS
2.5μmpix

Projection
2D Image was obtained

Ex=12.4 keV, z=867 cm

Grating x2
d=9.6 μm, f=0.2

CMOS 2.5 μmpix
GMAX0505

0.08"

preliminary
“Experimental” Simulation of Two Sources
z=92cm, Rotate the Optical Bench

Real Observations of a 8GeV Jet on the Earth

φ = 0.108"

2.16"

Merge Event Data
z=0.92m 光学台の向きを変えてデータ取得
イベントデータをマージ=2個の天体の観測模擬

φ_H=0.45", φ_V=0.0"
φ_H=0.0", φ_V=0.432"

φ_H=0.72", φ_V=0.0"
φ_H=0.0", φ_V=0.756"

2.16"
MIXIM is scalable in unit no and in d&z

\[ z = \frac{md^2}{\lambda} = 50cm \left( \frac{m}{2} \right) \left( \frac{d}{5\mu m} \right)^2 / \left( \frac{\lambda}{0.1nm} \right) \]

\[ \theta = \frac{fd}{z} = f \lambda / dm = 0.4'' \left( \frac{f}{0.2} \right) \left( \frac{\lambda}{0.1nm} \right) / \left( \frac{d}{5\mu m} \right) \left( \frac{m}{2} \right) \]
MIXIM-S (Small)
- $z=50\text{cm}$
- $\theta=0.4''$
- $d=5\mu\text{m}, f=0.2$

-P (Parasite)
- $z=10\text{m}$
- $\theta=0.09''$
- $d=22\mu\text{m}, f=0.2$

-Z (Zoom)
- $z=10\sim100\text{m}$
- $\theta=0.1''\sim0.01''$
- $d=71\mu\text{m}, f=0.1$

-L (Large/LISA)
- $z=2.5\times10^6\text{km}$
- $\theta=3\mu\text{arcsec}$
- $d=35\text{cm}, f=0.1$
Primary Target >mCrab almost Point-like Sources e.g. Nearby AGNs

Everything included in this 6 decades would be target of MIXIM
Circinus Galaxy(Sy2) Fe-Ka line simulation

$A_{\text{eff}} = 10 \text{ cm}^2$ (If we get Det. Layer of $20\mu$m, $A_{\text{geo}} = 24\text{ cm}^2$), $T_{\text{exp}} \sim 1\text{ Ms}$

Opening Fraction 0.5, Minimum Patter 0.2 Mask $z = 8.67\text{ m}$

Very Preliminary by K. Asakura

Background is not included
Jets are important target, of course.

Chandra X-ray Images of M87 from Press Release 2019
(Credit: NASA/CXC/SAO/B.Sinos)
Do we need X-ray observations around the Event Horizon after EHT?

• **X-ray vs Radio**

  Thanks inputs from Kawashima-san, Tazaki-san

  • Penetration power is highest for (hard) X-rays.
    • Optically thick gas in radio can be optically thin in X-rays.
    • AGNs with high accretion rate (not RIAF) can be targets for X-rays but not for radio (?).
    • Inner edge of a (standard) accretion disk, which is sensitive to BH spin, can be imaged only with X-rays (?). *Coronae*, too.

  • (Color) **Temperature** of the accreting matter can be measured only with X-rays.

  • **Elemental Abundance** and **Doppler Motion** (through Fe fluorescent lines) can also be measured with X-rays.

  • Enough room to diffraction limit for X-rays but not so for radio.

  • The event horizon was resolved in Radio but not yet in X-rays.

**X-ray would be complementary to Radio, at least**
Limitations Not like Mirrors

• No Collecting Power
  • Additional Collimator (0.1-1deg) is needed.
  • Eff. Area=Geo. Area x f x Det. Efficiency
  • Non Xray Background will be those for conventional collimator detectors

• Narrow “1-period” FOV

Many Technical Issues

• Attitude Determination must be better than the image resolution.
  • Conventional Star Trackers are not enough.
  • Techniques used in Astrometry may help.
  • Common Issue for super high angular resolution instruments

• Note: Attitude Control is not as severe as
  • X-rays through Grating goes Detector; tolerance of mm is allowed.
  • Formation flight case, fuel needed to control the grating satellite orbit may be a problem.

• Optical CMOS detection layer is currently thin, e.g. 5um.
  • .....
MIXIM FAQ

1. Is MIXIM interferometer?
   • In the sense that the Talbot Interference condition is the key. Multi slit camera employing the Talbot interference may be appropriate.

2. What is the FOV of MIXIM.
   • Folded image within the (additional) collimator is obtained. FOV is thus 0.1-1deg, while 1-folding-period is very narrow. If we use f=0.2 grating, just 5 times of Ѳ.
   • One bright point-like source within 0.1-1deg FOV is expected.

3. Effective Area of several cm\(^2\) is too small, isn’t it?
   • People observe >µCrab (Suzaku) >10nCrab (Chandra) sources with Telescopes with 100-1000cm\(^2\) effective area.
   • For MIXIM targets >mCrab, it should be enough
   • cf. We roughly estimate 0.1 c/MIXIM-unit/Crab with technical enhancement in next few years. 5 units, 5mCrab source need 0.5Ms to collect 10\(^3\) counts.

4. How can you obtain 2D image? Muti-Pin-Hole?
   • 1D units placed X and Y are baseline. 2D mask with larger opening is being designed.