The EUV Normal-Incident Telescope with an Adaptive Optics

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ABSTRACT

• We report some experimental results of our normal-incident EUV telescope tuned to a 13.5 nm band, with an adaptive optics.

• We confirmed the validity of our control and performed a 2.1 arc-sec resolution by both optical light and EUV.
Outline

• 1. Introduction
• 2. Telescope Design
• 3. AO System
• 4. Experiment
• 5. Summary
1. Introduction

In X-ray Astronomy, we can investigate very-hot objects and non-thermal energetic phenomena by taking Energy Spectra, Time Variations and Images.

- X-ray wave length
  - O-type Star δ Ori (CXO)
  - From Chandra Photo Album

- Time
  - X-ray Pulsar Cen X-3
  - Kohmura et al. 2001

- Radio Galaxy Cen A (CXO)
  - From Chandra Photo Album
1. Introduction

- X-ray Astronomy Satellite “Chandara” was launched in July 1999 and it has ~0.5 arc-sec resolution. This is the best telescope in the world.

- *Chandra* is providing us wonderful X-ray images and we are enjoying lots of science.

- However, the current achievement of the image quality is still far from the theoretical diffraction limit!
Celestial Objects

- AGN
- Jets
- SNRs
- SNe
- AGN-BHs
- Binaries-Jets
- CVs
- Stars
- Accretion Disks

Typical Distance:
- 1 kpc
- 1 Mpc
- 1 Gpc

Typical Size [km]:
- Log (Typical size)

Scale:
- 1 as
- 1 mas
- 1 μas
- 1 nas
Angular-sizes of BHs

<table>
<thead>
<tr>
<th></th>
<th>Mass (Msun)</th>
<th>D (kpc)</th>
<th>(m)</th>
<th>Rs (au)</th>
<th>(µ as)</th>
<th>Shadow Size (µ as)</th>
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<td>0.001</td>
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<td>1.97E-08</td>
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<td>8</td>
<td>7.67E+09</td>
<td>5.11E-02</td>
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<td>M31</td>
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<td>800</td>
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<td>9.44E+12</td>
<td>6.29E+01</td>
<td>3.91</td>
<td>19.54</td>
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</table>

Ultimate objective is a BH-imaging. 1 µ-arc sec resolution is required.

This is currently almost impossible.

Takahashi & Mineshige (2003)
Without mentioning the BH imaging, if we have a diffraction limit X-ray telescope with 1 m diameter, the resolution is \( \sim 1 \) milli-arc-sec.

We can observe many of cosmic jets, binary motion, nearby stars……

We started development of a m-arc-sec resolution telescope.

X-ray milli-arc-sec Project (X-mas Project).
2. Telescope Design: What is the problem?

Requirement of Small-scale Roughness: several Å  

Requirement of Large-scale Figure Error: ~1 nm

We must correct only large scale figure error by thermal and gravitational distortion. This requires only slow control. This is not a case of ground base AO telescopes. They need to correct the atmospheric and need very fast control.

We are applying two ideas.

[1] continuous monitoring of the figure error

[2] adaptive optics system
A normal incident telescope is easier than the grazing incident telescope on a fabrication point of view, and on having a large effective area.

Possible precision of a simple shape measurement is ~ nm.

13.5nm band is currently best choice.

Because Mo/Si Multi-Layers has more than 70% reflectivity for the normal incident mirror.
The measurement of the EUV wave form is difficult. An optical light is used as a reference wave.

Correction of the wave form as approaching to a target wave form.
• The paths of the reference light and the EUV are different from each other.
• We modify the target wave form
• Optimum target wave from is derived and control the system to have a good image for EUV.
4. Experiment: Telescope

The measurement of the EUV wave form is difficult. An optical light is used as a reference wave.

- Optical Light or EUV (LPS → Primary Mirror → DM → CCD)
- Reference wave (optical laser → primary mirror → DM → wave front sensor)

Xmas Telescope

- Primary mirror
- Wave front sensor
- Optical Laser for reference
- Deformable Mirror
- Glass
- Zr filter
- 512x512 CCD

HASO32 Shack-Haltmann
32×32 micro-lenses
512×512 CCD

Thickness: 150nm
Transmission: ~60% @ 13.5nm
Transmission: ~0.01% @ Optical
Supported by a mesh with interval: 332μm
Thickness: 31μm

Thickness: ~1 mm
Optically transparent
X-ray opaque

Wave length: 6 6 3 nm
Spot size: 1μm
4. Experiment : Set up

- Wave front sensor
- Primary Mirror
- Deformable Mirror
- Optical Laser
- For reference
- Xmas Telescope
- Zr filter or Glass
- Debris Shield
- Beam Expander
- Mechanical Shutter
- High Power
- YAG Laser
- Optical Laser Unit
- Cu Target
- Experimental Configuration
- Lens
- Debris Shield
- Shutter
4. Experiment: Closed Loop Control with Optical Light

**Before Control**

Alignment Laser (663 nm)
- RMS: 0.150 μm
- P.V.: 0.599 μm

Pixel resolution: ~4.44 arcsec

**During Control**

Alignment Laser (663 nm)
- RMS: 0.033 μm
- P.V.: 0.169 μm

Pixel resolution: ~2.67 arcsec
4. Experiment: Modify target wave form

Target Wave Form

<table>
<thead>
<tr>
<th>収差名</th>
<th>係数 [um]</th>
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<tbody>
<tr>
<td>tilt at 0°</td>
<td>-16.45</td>
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<tr>
<td>tilt at 90°</td>
<td>-1.96</td>
</tr>
<tr>
<td>focus</td>
<td>-4.466</td>
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<tr>
<td>astigmatism at 0°</td>
<td>0</td>
</tr>
<tr>
<td>astigmatism at 45°</td>
<td>0</td>
</tr>
<tr>
<td>coma at 0°</td>
<td>0</td>
</tr>
<tr>
<td>coma at 90°</td>
<td>0</td>
</tr>
<tr>
<td>spherical</td>
<td>0</td>
</tr>
<tr>
<td>etc...</td>
<td>0</td>
</tr>
</tbody>
</table>

Alignment Laser (663 nm)

By modifying the target wave form, the resolution becomes better. The resolution is roughly consistent with the diffraction limit of the optical light.

Resolution: ~2.67 arcsec

Resolution: ~2.13 arcsec
4. Experiment : Imaging Experiment with EUV

LPS - EUV(13.5nm)  Diffraction Limit : 0.042 arc-sec

With spherical target wave form

With modified target wave form

A little improvement but not enough performance
## 5. Summary : Result

<table>
<thead>
<tr>
<th></th>
<th>Visual(532nm)</th>
<th>EUV(13.5nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.A.O.</td>
<td>A.O. with Spherical target</td>
</tr>
<tr>
<td>Angular Resolution(arc-sec)</td>
<td>5.69</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>3.10</td>
<td>2.6</td>
</tr>
</tbody>
</table>

### Possible Cause of the poor performance

1. More precise primary mirror
   - Now we are polishing a new mirror.
2. Too large pixel size of the CCD
   - We ordered a new small pixel CCD
5. Summary

- An EUV AO-telescope is working now in our laboratory.

- We applied a closed Loop control using modified target, taking into account of the light path difference.

- The best resolution of the optical light is ~2.1 arc sec, which is roughly diffraction limit.

- In the EUV experiment, the resolution is still far from the diffraction limit, and further improvement is going on.