Adaptive X-Ray Optics with a Deformable Mirror

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ABSTRACT

We are developing a soft x-ray telescope with an adaptive optics system for future astronomical observation with very fine angular resolution of an order of milli-arc-second. From a technical point of view, we are trying to develop a normal incident telescope with multi layers. Thus the wavelength is limited to be around 13.5 nm with a band pass of roughly 1nm. Since the x-ray telescope must be installed on a satellite, a stable conditions of temperature, gravity etc, can not be expected. Therefore, we investigate to use an adaptive optics system using an optical light source attached in the telescope. In this paper, we report our present status of the development.

The primary mirror is an off-axis paraboloid with 80 mm effective diameter and 2 m focal length. This mirror has been coated with Mo/Si multi-layers. The reflectivity of the 13.5 nm x rays is ranging from 35% to 55%. We use a deformable mirror for the secondary mirror, which has also been coated with Mo/Si multi-layers. This mirror consists of 31 element-bimorph-piezo electrodes. The surface roughness of the mirror is ~6 nm rms. The reflectivity of the 13.5 nm x rays is roughly 65%.

The adaptive optics system using an optical laser and a wave front sensor has been performed. We are using a shuck-hartmann sensor (HASO 32) with a micro-lens array and a CCD. A pin hole with one micron diameter is used for the optical light source. The precision of the measurement of the wave front shape is a few nm.

X-ray exposure test is now conducting, although the optical adaptive optics system is not yet installed. The x-ray detector is a back illumination CCD. The quantum efficiency for 13.5 nm x ray is ~50%. The pixel size is 24 micron square. X-ray source is an electron impact source with an Al/Si alloy target. We confirmed that the x-ray intensity around 13.55 nm is bright enough for our experiment. The imaging performance is now trying to improve and the adaptive optics system will be installed in this year.

Keywords: EUV, X-Ray, Telescope, Adaptive Optics, Multilayers

1. INTRODUCTION

We are developing an ultra high precision X-ray Telescope, named X-ray milli-arc-sec Project (X-mas Project), as a future space mission.

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The X-ray Astronomical Satellite “Chandra”, launched in 1999, is providing us wonderful X-ray images with an angular resolution of ~0.5 arc-sec and we are enjoying lots of important scientific results [1]. However, the current performance of the image quality of X-rays is still far from the theoretical diffraction limit. The diffraction limit of the telescope is determined by the telescope diameter and the wavelength. If we have a diffraction limit X-ray telescope with ~1 m diameter, the resolution of the order of 1 milli-arc-sec (mas) can be achieved. The most interesting astronomical object with ~1 mas resolution is the cosmic jets. Some jets, with 1 arc-sec size have been observed with Chandra, while the radio interferometer can observe the jets with 1 mas resolution. If we can compare the images of jets with 1 mas resolution, we can approach the collimation mechanism of the jets and the relation of the structure of jets and the magnetic field.

In order to achieve an X-ray telescope with 1 mas resolution, the requirement of the small-scale roughness of the X-ray optics is roughly several angstrom. This is rather easy. The requirement of the large-scale figure error is less than wavelength and is roughly 1nm or less. This value is almost impossible. Since the X-ray telescope must be equipped on a satellite, the thermal distortion and the gravitational distortion make a deformation of more than 10 nm. We are now trying to overcome this difficulty by applying two ideas. One is the monitoring of the optics with optical light. The other is the adaptive optics system. In this paper, we report our current status of this project.

2. TELESCOPE DESIGN

In order to have large effective area, a normal incident configuration is easier than a grazing incident telescope. For 13.5 nm wave length, Mo/Si multi-layers have more than 70 % reflectivity for the normal incident reflection [2, 3]. Also, the possible precision of the measurement of the shape of the mirror is a few nm. Thus 13.5 nm band is the best choice for the telescope using current technique. Figure 1 is the design of a test telescope. This is slightly modified from the old design [4, 5, 6], where the X-ray optical separation filter was used. Although we had tried to develop the X-ray optical separation filter, now we are considering a new configuration without x-ray optical separation filter.

![Figure 1. The current design of the laboratory test telescope.](image-url)
In front of the x-ray generator, a test pattern is installed, which is now a simple mesh. The image of the test pattern will be focused on the CCD. The optical blocking filter is required in order to block the optical light from the X-ray generator. The primary mirror was made by Elide polishing [7]. Its shape is an off-axis paraboloid with an effective diameter of 80 mm and focal length of 2000 mm. Mo/Si multi-layers were coated on the mirror surface and the reflectivity was measured at 13 positions. The reflectivity is a little worth, but is ranging from 30% to 50%. The diffraction limit of the image size of 80mm diameter for the 13.5nm wave length is ~42 mas.

The secondary mirror is a deformable mirror. The deformable mirror is constructed by 31 element bimorph piezo-electric plates (BIM31 mad by CILAS) [8]. One element is at the center, and six elements make a circle around the center and on the seconds and 3rd circle 12 elements are installed. The elements in the 3rd circle are out of the effective area and they will make the boundary shape of the effective area. The bimorph piezo-electric plate is a two-layer-piezos with the opposite polarity. Thus this plate makes a curvature of concave or convex shape. The effective diameter is 55 mm. The performance as a single component of the deformable mirror is demonstrated by making a flat plane. Currently 5.26nm-rms of the flatness has been achieved using the feedback system with the Zygo interferometer.

The optical laser is installed near the X-ray pass. A pin hole with 1 micro-m diameter is used. The optical lights go along similar light pass to that of X-rays, but they finally enter into the wave front sensor. Comparing the measured wave front of the optical light with the expected wave front by the condition of the best performance for the X-rays, the deformable mirror is controlled as an adaptive optics.

The wave front sensor is a shack-hartmann sensor (HASO 31; Imagine Optic) made by a micro-lens array and a CCD [9]. The positions of the images of each micro-lens array are analyzed and the wave front shape is calculated. We have been measured the precision of the image position determination with the CCD and confirmed that the precision is less than 1/100 of the pixel size. The size of the CCD pixel is 10µm, and the position determination accuracy is less than 0.1µm in r.m.s [5]. The ideal spherical waves were exposed to the wave front sensor and checked the measured wave front. The detected shape of the wave front was ideally spherical within the error of 2nm rms, if the CCD signal was enough high [4].

2-1. X-ray generator

For the test experiment with 13.5nm EUV lights, we developed an x-ray source. The x-ray generator is a Manson Ultrasoft X-ray Source. This is an electron impact X-ray source. The bremsstrahlung continuum and characteristic X-rays of the target material are emitted. We are using Al/Si alloy with Si 16.4% contents, for the anode cap and we expect the 13.55nm EUV by Si L transition.

The emission of the 13.55 nm emission line is confirmed by the following experiment. The x rays from the Manson source are first reflected by a Mo/Si multilayer with 2d=28nm and Si-L lines are extracted. This is performed by homemade monochromator as shown in figure 2. This monochromator is a simple one-time reflection by a multilayer installed in the triangle chamber at the rotational axis. The x-ray source, shown in the right side of the figure, is attached on the rotational arm and the exit beam position, at the left side of the figure, is fixed. The motors and the 0-2 θ rotational table are in the outside of the vacuum. The flexible bellows make it possible to rotate the multilayer and the x-ray source. The calculated reflectivity of the multilayer for 33deg incident angle is shown in figure 3. The reflectivity of P-polarization and S-polarization are both shown. The reflectivity is expected to be more than 50% for Si-L line. Nearby continuum x-rays are also reflected.
Figure 2. The hand-made monochromator with the Manson Ultra-soft X-ray source.

Figure 3. The calculated reflectivity for the Mo/Si multilayer installed on the home-made monochromator for 33 deg incident angle. The Si-L line of 13.55nm wave length and nearby continuum x-rays are reflected. The thick line is for S polarization and thin line is for P polarization. The surface roughness is assumed to be 0.
Figure 4. The inside of vacuum chamber for the reflectivity measurement.

Figure 5. The reflectivity of the multilayer for 13.55nm Si L lines as a function of the incident angle. The points are measured values and the solid line is the calculation for roughness of 10 Å.
The monochromatic x-ray beam is introduced into the other vacuum chamber. The inside of the vacuum chamber is shown in figure 4. The beam coming from bottom of the figure is reflected by a Mo/Si multilayer with 2d~26nm. The reflected beam is detected by a back side CCD. The multilayer and the CCD are installed on a θ−θ table. The reflectivity of the multilayer as a function of the incident angle is shown in figure 5. The peak around 33 deg of the reflectivity is the clear evidence of the 13.55nm x-rays. The reflectivity with ~30% is measured. In figure 5, a simulated reflectivity for no-polarized X-rays is also plotted, where the surface roughness of 10Å is assumed.

3. TELESCOPE ASSEMBLY

3.1. Vacuum chamber

All the telescope components must be installed in a vacuum chamber. The picture of the current set up is shown in figure 6. The vacuum chamber is constructed by three parts according to the required diameter. The vacuum chamber is now on a vibration isolation table. Although the final design of the X-ray telescope is for the parallel beam from the infinite distance, in this experiment the X-ray source is put at the 4350 mm away from the main mirror. The deformable mirror is installed around the center of the vacuum chamber. Finally a back side CCD camera is attached at the left end of the chamber.

3.2. Optical Blocking Filter

In current telescope configuration, the monochromator is not used. Therefore, the optical light from the X-ray source must be blocked for the experiment. In order to block the bright optical light, we used two pieces of Zr filter with 1500Å thickness. The optical transmission of one filter is roughly $5 \times 10^{-6}$[10]. Thus two filters are sufficient to block the optical light. The 13.5nm X-ray transmission of the Zr filter was measured by a synchrotron orbital radiation ring in the Photon Factory of KEK[11,12,13]. Figure 7 shows the measured transmission as well as a simulated transmission of 170nm thickness[14]. The X-ray transmission at 13.55nm (91.5eV) is 45%. Thus the transmission of two filters is 20%.

Figure 6. The vacuum chamber for the experiment.
Figure 7. The measured transmission of the Zr filter. The simulation for 170nm thickness is also plotted.

3.2 Optical Image

We first took an optical image of the X-ray source, which is the anode cap of the Manson source shined by the filament. The adaptive optics system has not yet worked in the telescope. Thus a simple direct image is taken by the back side CCD. Any tuning of the focus etc. has not yet done. The image is shown in figure 8. The image shows a

Figure 8. The optical image of the anode cap. No adaptive optics is applied.
pattern on the anode cap, which diameter is 9mm. The center spot on the anode cap can be seen as a dark region, which diameter is roughly 1mm. Thus the image resolution is roughly 0.05mm. The anode cap is 4350mm away from the primary mirror. The angular resolution is 2.4 arc sec, which is a little worse than the diffraction limit of this system with 80 mm diameter for the 500 nm wave length.

4. CONCLUSION

Now we are starting the vacuum test of the normal incident X-ray telescope. For the first step, an optical image of the anode cap is obtained with appropriate resolution. The X-ray source for 13.55nm is almost ready for the experiment. The closed loop performance has been confirmed by the optical system, separately. The next step is the final X-ray test with optical closed loop system.

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