Optimization of geometrical design of nested conical Wolter-I X-ray telescope

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Optical design of nested conical Wolter-I X-ray telescope covering energy band from 1 to 30 keV is investigated systematically. Recurrence relation of the nested structure is deduced, and the impact of the initial parameters on the performance is analyzed. Due to the need for hard X-ray astronomical observations in China, the initial structure is presented, for which six groups of W/B$_4$C aperiodic multilayer coatings between the innermost and the outermost shell of the mirror are designed. The effective area, resolution, and field of view are calculated in the simulation. The results show that the effective area can achieve 71 cm$^2$ and the field of view can achieve 13′ at 30 keV. The resolution is estimated to be $\sim 10''$ in half-power diameter.

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The cosmic X-ray background (CXB) resides in the 0.1 to 100 keV energy range. Deep X-ray surveys have resolved CXB around 1 keV into a population of discrete sources nearly entirely composed of active galactic nuclei (AGN)[1]. In addition, CXB in the 2 to 10 keV range has been completely resolved by Chandra and XMM-Newton telescopes when the sky flux is dominated by extragalactic emission. The main contributors are thought to be absorbed and unabsorbed AGNs with a mixture of quasars and narrow emission line galaxies[2,3]. The Chandra telescope, which is composed of four nested Wolter-I mirror pairs coated with a single iridium layer, could achieve the effective area of 800/400 cm$^2$ at 0.25/5 keV and resolution of 0.5''[4,5]. The XMM-Newton telescope, which consists of 58 gold-coated nested Wolter-I mirrors, could achieve the effective area of 1 475/580 cm$^2$ at 1.5/8 keV and resolution of 16''[6]. Many X-ray sources above 10 keV are available, such as the peak of CXB at ∼10 keV energy is established. The recurrence relation of the nested structure is deduced, the principle of selecting initial parameters is proposed, and corresponding aperiodic multilayer mirror is discussed.

In 1952, Wolter demonstrated a type of optics in which a paraboloid and hyperboloid combination was mounted in a coaxial and confocal arrangement. X-rays utilized two successive reflections from the paraboloid and then the hyperboloid to focus the image[16]. To overcome the difficulty in the fabrication of highly aspherical mirrors, conical mirrors were suggested in lieu of precisely curved paraboloidal and hyperboloidal surfaces. Parallel incident X-rays could not focus the image, but formed a blurred circle[13].

The diagram of the nested conical Wolter-I X-ray telescope is shown in Fig. 1. A rectangular coordinate system with origin $O$, ordinate $r$, and abscissa $Z$ along the opposite direction of incident lights was established. X-ray incidents along the -Z direction are then reflected twice along two groups of rotating cone to focus on origin $O$. Here, $f$ is the focal length from the center of secondary mirror to the focal point, $t$ is the thickness of the mirrors, $L_P$ is the length of primary mirror, $L_h$ is the length of secondary mirror, and $\theta_N$ is the grazing incident angle of the $N$th mirror. The primary and secondary mirrors have the same grazing incident angle. Here, $r_N$ is the radius of the $N$th secondary mirror’s end point and $R_N$ is the radius of the $N$th secondary mirror’s
The angle radius of spot diagram imaged by the ray in-determined by the focal length \( f \) and the geometrical area can be expressed by

\[
A = \sum_{N=1}^{n} 2\pi \cdot r_N \cdot L_P \cdot \tan \theta_N.
\]

The angle radius of spot diagram imaged by the ray incident to the \( N \)th mirror can be expressed by

\[
\theta_{\text{spot}} = a \tan \frac{r_N - (f - L_h)}{f} \cdot \tan(4\theta_N).
\]

Equations (2)–(6) indicate that the effective area and the resolution are decided by the focal length \( f \), the radii \( r_N \), the mirror lengths \( L_P \) and \( L_h \), and the mirror thickness \( t \). The choice of initial parameters depends on their influence on the performance and the laboratory conditions.

According to the mandrel in our laboratory, the outermost radius \( R_{\text{out}} \) was set as 85 mm and the innermost radius was set as 30 mm. The focal length was chosen as 4 m considering the volume and the weight of satellite that can now be provided. The remaining parameters of mirror thickness and mirror length were discussed, as shown in Figs. 2 and 3. The length of the primary mirror \( L_P \) and the length of the secondary mirror \( L_h \) can be calculated by

\[
L_h = \frac{L_P \cdot \cos 3\theta_N}{\cos \theta_N},
\]

for all axial rays incident to the primary mirror that are received by the secondary mirror. Thus, only \( L_P \) needs to be discussed.

Figure 2 shows the effects of mirror thickness on the geometrical area and the resolution with \( L_P \) of 100 mm. The geometrical area decreases from 143 to 99 cm\(^2\), whereas the resolution expressed by the half-power diameter (HPD) does not change with the increase of mirror thickness from 150 to 390 \( \mu \)m. Less thickness of the mirrors is a crucial factor to obtain a larger effective area. Mirrors with thicknesses of 400 and 200 \( \mu \)m were available in our laboratory; therefore, mirrors of 200-\( \mu \)m thickness were chosen.

Figure 3 shows the effects of mirror length on the geometrical area and the resolution with the mirror of 200-\( \mu \)m thickness. The resolution decreases from 9" to 26", whereas the geometrical area increases from 131 to 173 cm\(^2\) with increased mirror length from 100 to 300 mm.
The enlargement of the geometrical area by lengthening mirror results in a loss of resolution. Therefore, the choice of mirror length must balance the geometrical area and the resolution, and must also rely on the actual engineering. A large geometrical area can be obtained by thinner mirrors; therefore, we chose the mirror length of 100 mm to meet the resolution and the requirements of the system.

With this group of parameters, the initial structure could be determined. In the nested structure were 101 shells of mirrors. From outer to inner, the interval between two adjacent shells gradually decreased. The interval between the first and the second shells of the mirrors was 0.7313 mm; however, between the 100th and the 101th shells of mirrors, the interval was 0.3908 mm. The change of grazing incident angle between two adjacent shells of mirrors was also gradually decreased from 0.0026° to 0.0014°.

The effective area can be described as the product of total geometrical area and mirror’s reflectivity:

\[ A_{\text{eff}} = \sum_{N=1}^{n} 2\pi \cdot r_N \cdot L_P \cdot \tan \theta_N \cdot R(E, \theta_N), \quad (8) \]

where \( R(E, \theta_N) \) is the reflectivity of the multilayer coating related to the X-ray energy and the grazing incident angles. Clearly, the high reflectivity \( R \) becomes the key point if a large effective area of the X-ray telescope is pursued. For X-ray observation, mirror surfaces should be coated by a single metal layers or multiple layers in order to enhance reflectivity[5,12]. A single metal layer is adequate for early X-ray observations below 10 keV[5]. However, because the scientific objectives extend to the hard X-ray region, the single metal layer does not have sufficient reflectivity above 10 keV when the grazing incident angle becomes relatively high. As shown in Fig. 4, the Au single layer has nearly no reflectivity in the hard X-ray region above 15 keV when the grazing incident angle is 0.3°. Compared with single layer and periodic multilayer coating, the aperiodic multilayer coating has high throughput in hard X-ray region and high reflectivity in a wide energy band. Thus, an aperiodic multilayer coating is preferred for the 1 to 30 keV X-ray surveys.

The flatness of reflectivity curve and integrated reflectivity are of concern with regard to multilayer coatings.

Fig. 6. Spot diagram in the focal plane.

However, for wide-band aperiodic multilayer coating, too large region of grazing incident angle will cause reflectivity to become drastically reduced, even to zero. According to Eq. (1), an aperiodic multilayer coating was designed for use in the grazing incidence angle region of 0.1° and 0.3° [18]. W/B₄C combination was selected as the layer materials, which has been confirmed to have good performance up to 70 keV. The grazing incident angle of 0.1° to 0.3° was divided into six groups and optimized for each group, as shown in Fig. 4. For all the mirror groups, the interfacial roughness between W and B₄C was set to be 0.45 nm. Figure 4 shows that the reflectivity of the first group, for which the grazing incident angle is 0.15°, features an excellent uniformity and average reflectivity of above 80% in energy region of 1 to 30 keV. When the grazing incidence angle was increased, the reflectivity of the following groups decreased from 65% to 37%. Mirrors in the same group were coated with an identical multilayer design.

By using the initial structure mentioned above, the performance simulation would give the effective area, the resolution and the field of view. In Fig. 5, the effective area is plotted against X-ray energy from 1 to 30 keV. The figure shows that effective areas of 115 and 71 cm² were achieved at 10 and 30 keV, respectively.

The image quality and the resolution were evaluated by the spot diagram, as shown in Figs. 6 and 7. The blank sectors in the spot diagram were caused by the support structure of mirrors. The angular resolution was calculated to be 10″ in HPD, with no consideration of tolerance.

The nested conical Wolter-I structure features a constant spatial resolution across the field of view. The field
of view was defined as the off-axis angle $\alpha$, at which the effective area decreased to one half of its on-axis value\cite{12}. Figure 8 shows the changes of spot diagram in the focal plane as the off-axis angle $\alpha$ changed. With the off-axis angle $\alpha$ changed, the spot diagram shifted to both sides of the original. The $X$ width of spot diagram did not change within 0.4 mm, whereas the $Y$ width increased from 0.4 to 2 mm. Statistics of the effective efficiency as off-axis angles changed at 2 and 30 keV was shown in Fig. 9. The field of view was achieved as 16′/13′ at 2/30 keV, respectively.

In conclusion, the optical design of nested conical Wolter-I X-ray telescope is investigated. The radius and grazing incident angle of inner surfaces can be calculated shell-by-shell with specific outermost radius and focal length. The mirror length and the mirror thickness are determined through their impact on the geometrical area and the resolution. With focal length of 4 m, outermost radius of 85 mm, mirror length of 100 mm, and mirror thickness of 200 μm, 101 shells of mirrors are constructed. For the energy region of 1 eV to 30 keV, a W/B$_4$C aperiodic multilayer mirror is suggested and designed. The effective area and the field of view are simulated to be 71 cm$^2$ and 13′ at 30 keV, and the resolution was estimated to be 10″ with no consideration of tolerance. The effects of tolerance, including figure error, alignment error, and other possible errors, will be discussed in our next work, which can provide basis for the replication of mirrors and alignment of the system.

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