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On X-ray telescopes in general and the *Athena* optics in particular

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ABSTRACT

The optical design of the most common type of X-ray telescopes is reviewed in this contribution and the imaging properties of these are discussed. Then the newest mostly European large mission, *Athena*, is presented and some of the most important properties imaging-wise are reviewed. Finally the science program for *Athena* is described where the emphasis is on the cosmic web and the population of AGNs.

1. Introduction

The most important source of information about the universe is photons from the celestial objects. The photon spectrum and time variability can tell a lot about the physical nature of the source. What is between us and the source can in many cases be investigated by the scattering and absorption of the photons when revealed in the energy spectrum.

The visible spectrum was for a long time the only part of the entire electromagnetic spectrum that was accessible to observation but the advent of new detection systems and the access to outer space broadend the range to include virtually all wavelengths. Large antennas and telescopes have been constructed both on the surface of the Earth and in space where the absorption in the atmosphere is avoided. For X-rays – and gamma rays – this is essential since all such radiation from the outer space is absorbed in the atmosphere.

Since the first non-solar X-ray telescope in space on NASA's *Einstein* satellite (launched November 1978) about twenty X-ray telescopes have been flown on satellite missions.

The special feature for X-rays is that reflections can only happen at grazing incidence i.e. at very shallow angles[1] otherwise the rays will simply be absorbed in the material. This puts severe constraints on the design of X-ray telescopes.

2. Design of X-ray telescopes

The first simple 'telescope' for astronomy in the X-ray range was proposed in 1960 by Giacconi and Rossi [1]. It is a single reflection X-ray concentrator with no real imaging for which two reflections are required.

The next step was to take advantage of the Wolter 1 [2] system with two reflections originally suggested for X-ray microscopes. Its use for celestial observations was first proposed by Van Speybroeck [3] in 1972. Fig. 1 shows how rays are first reflected on the inner side of a paraboloid and then on a confocal and co-axial hyperboloid focussing to the other focal spot. Since only small angles can be used a nesting of the reflecting surfaces, normally called X-ray mirror shells, increases the projected active surface. Simple considerations (see the appendix) lead to the conclusion that the two angles of reflection should be equal for maximal reflectivity when the coefficient of reflectivity is a monotonically decreasing function of the angle.

Fig. 2 shows an example of an X-ray mirror realization, namely the telescope on the Japanese *Suzaku* mission.

2.1. Mirror shape and imperfections

The thinner the mirror shells the more can be fit into the telescope and minimize the loss of photons hitting the shell edges. On the other hand rather thick substrates are required to obtain the geometrically correct surfaces.

The mirror shells are placed in a support structure where they may bend by an internal stress or by forces imposed by the structure, perhaps by mechanical inaccuracies or by thermal changes. Such long scale perturbations will have an influence on the Point Spread Function (PSF, see Section 2.3). Some direct knowledge might be acquired by pre-launch calibrations maybe even during telescope building as was

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[1] Here and throughout the paper the term 'reflection angle' refers to the grazing (or glancing) angle between the ray and the mirror surface.

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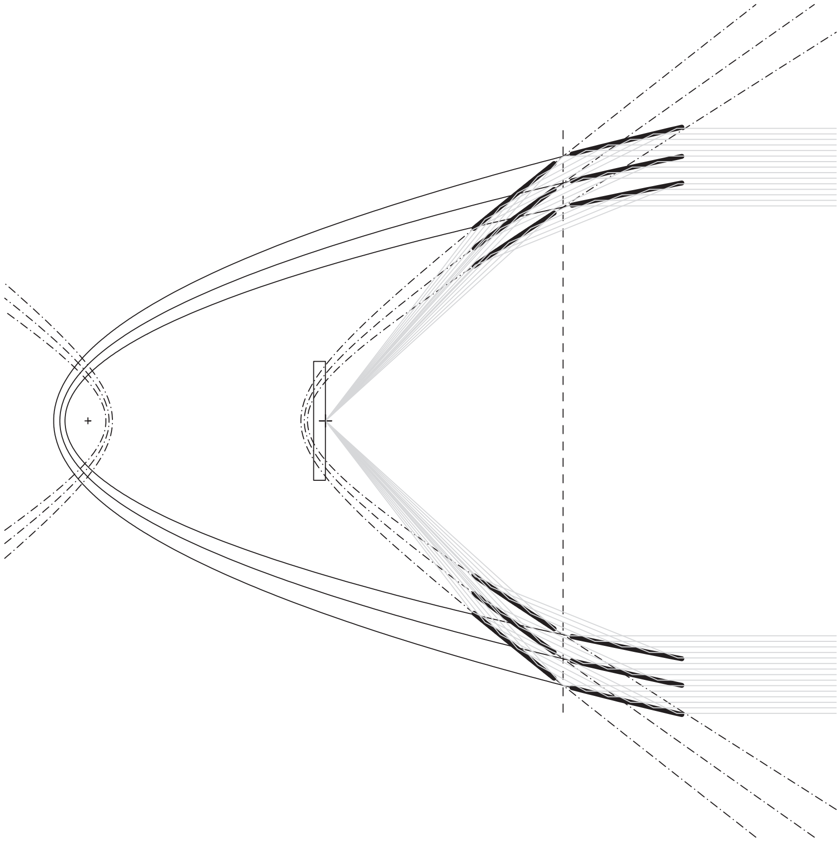

Fig. 1. A conceptual sketch of a nested Wolter 1 configuration. The paraboloids are shown with solid lines, the hyperboloids in dash-dot lines. The two foci are marked by crosses. The physical reflecting surfaces are indicated with the thick parts of the cone sections. The incoming rays from the right side are indicated with grey lines and a detector is shown as a rectangular box. The central plane of the optics is indicated with a dashed line from which the focal length is measured to the focal plane (detector surface).

the case with *NuSTAR* [4]. In the raytracing such long scale perturbations can be handled by look-up tables with information on individual mirrors.

Building telescopes with near perfect paraboloid/hyperboloid mirror shapes is very expensive and a conical approximation to these surfaces is used in quite a number of missions. One advantage is that the thin mirror substrates are only bent in one direction which is a great simplification in the production. Very often the figure errors and scattering (see Section 2.2) will be more important for the angular resolution than the effect of the approximation.

Fig. 2. A realization of an X-ray telescope: The *Suzaku* telescope.

2.2. Scattering

True specular reflection where the outgoing angle equals the incoming angle only happens for a fraction of the photon reflections. Due to the short wavelength of the X-rays and the surface roughness of the mirrors a scattering away from the specular direction will often happen [5]. The assumption is made that the photons always leave the point of reflection in the plane defined by the surface normal and the ingoing direction. This is a very good approximation due to the small angles.

With a good description of the mirror surface with respect to roughness, not only in the top layer but in case of a multilayer coated surface also for the layer interfaces the scatter angle distribution can be calculated analytically [6]. In many cases such computations must be checked by actual scatter measurements from sample mirror surfaces.

In the raytracing code MT_RAYOR [7] the scatter angle is sampled from a distribution that is a function of photon energy and grazing angle. This is accomodated with the help of look-up tables to be able to include measured results and to avoid being dependent on a specific scatter model.

2.3. The point spread function

The density of photons from a point source at infinite distance in the focal plane is described by the PSF and it depends on the source position in the Field-of-View (FOV) and on photon energy. In Fig. 3 examples are given for a Wolter 1 telescope by raytracing of a point source (see also Werner [8]) with various off-axis angles. The focal length is 12 m and the modelled telescope has a perfect geometry, tight nesting, and neither scattering nor mirror deformations are included to show the intrinsic comatic aberrations for off-axis sources.