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Grazing incidence at work: an outreach project to demonstrate the X-ray optics behaviour using the nested mirrors developed for the *BeppoSAX* X-ray satellite

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ABSTRACT

BeppoSAX was an Italian-Dutch satellite designed for X-ray observations, launched in 1996 and deactivated in 2002. It was the first satellite to precisely localize the Gamma Ray Bursts and to detect the X-ray emission due to the afterglow, a breakthrough discovery for high energy astrophysics that eventually placed such events at extra-galactic distances after many debates in the previous years. On board of the satellite there were four identical X-ray imaging telescopes based on grazing incidence mirrors, ranging between 1-10 keV in energy and with a spatial resolution <1 arcmin HEW. In order to limit the costs of the telescopes, the optics were assembled using nickel nested mirrors replicated via electroforming using masters. During the development of the instruments of *BeppoSAX*, two qualification models of the grazing mirrors were assembled and used for tests at various X-ray facilities; they are now in storage in Milano (Italy) at the INAF-IASF Institute and Brera Observatory. In this paper, we describe the setup we have built in order to use these models for an outreach program. The aim of this effort is to illustrate to students and teachers of secondary schools how a grazing mirror for X-ray astronomy works. A first~~,~~ basic experiment shows the reflection of light at normal incidence: using two small face-to-face parabolic reflectors, a powerful lamp positioned in the focus of the first parabola can light a match fixed in the focus of the other reflector. A second experiment uses the nested mirror to show how to deflect photons using grazing incidence. In this case a plane wave, created with a light source and a Fresnel lens, enters in the front of the Beppo SAX optics made of several nested mirror shells and is focused exactly as for X-rays.

Keywords: X-ray astronomy, *BeppoSAX satellite*, grazing incidence, X-rays, outreach, optics

1 INTRODUCTION

The observation of the Universe in X and gamma rays was pioneered by Italian scientists, Giuseppe Occhialini, Bruno Rossi and Riccardo Giacconi, starting with balloons and rockets. On the exceptional school of these scientists, research institutes and industries have born in Italy with the goal to develop a scientific satellite. The dream became real on 1996 April 30th, when the X-ray satellite SAX (Satellite per Astronomia X), named *BeppoSAX* after launch in honor of Giuseppe (Beppo) Occhialini, was launched from the Cape Canaveral Station. The mission was a program of the Italian Space Agency (ASI), with participation of the Netherlands Agency for Aerospace Programmes (NIVR), and gave great results on the high-energy astrophysics. The trump card was the large spectral range, from 0.1 to 300 keV, giving the opportunity to study astronomical sources emitting in a broad X range. The satellite was able for the first time to observe a few sources (Blazars) in which the peak of the synchrotron emission reached 100 keV, showing the presence of cosmic rays with energies in the TeV range. Moreover, it could, for the first time, measure the position of the gamma ray bursts (GRB), on rapid time scale, with the precision of few arc minutes. The GRB's afterglow was also detected for the first time: this is of primary importance as the evolution of the spectral components (like the fluorescence line of the Fe K) is essential to understand the GRB origin. Guided from the alert signals given by *BeppoSAX* to other telescopes, both ground and space based, the afterglow could also be observed in an even broader spectral range. In this way, light was casted on those strange ray bursts, identifying them as arising from very distant galaxies, releasing energy as large as the one of the mass of our Sun converted into light in a very short time.

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BeppoSAX carried on board two different types of instruments:

- Four Narrow Field Instruments (NFI) with high sensitivity, designed to enable observations on more than three decades on weak sources; among these, MECS (Medium Energy Concentrator Spectrometers) and LECS (Low Energy Concentrator Spectrometer) were using grazing incidence telescopes with double cone geometry;
- Two Wide Field Cameras (WFC) consisting in coded mask proportional counters, to monitor large areas of the sky looking for transient phenomena.

During the development of the grazing incidence telescopes, two qualification models were assembled and used for tests at various X-ray facilities; they are now in storage in Milano (Italy) at the INAF-IASF Institute and Brera Observatory. In this paper, we present an outreach project, based on these models, to illustrate how a grazing mirror for X-ray astronomy works. Since X-rays are invisible to human eye, visible light was used to show the properties of these telescopes. First normal reflection is explained with a set of two parabolic mirrors, then grazing reflection is addressed, using a Fresnel lens and a SAX module.

To our knowledge, this is the first time that X-ray telescopes are used for outreach. The program is meant both for students and teachers of secondary schools, and for the public visiting our institutes in the Milano area and science outreach events.

2 NORMAL INCIDENCE EXPERIMENTS

2.1 The setup

The first experiment is a simple setup to illustrate the normal incidence reflection of light rays.A source is positioned in the focus of one parabolic mirror to obtain a parallel beam with this first reflection; the beam undergoes a second reflection on another parabolic mirror. At its focal point, a screen can be positioned to image the source. If a match replaces the screen, and the light source power is increased, the match is burnt.

For the selection of the parabolic mirror, a light, robust and cheap system was preferred, therefore glass mirrors were avoided. A good compromise was found with a pair of 12-inch diameter parabolic reflectors (Edmund Scientific, part no. 53-875); they are made in aluminum without coating, and their surface is rough but sufficiently reflective for our experiment. A summary of their characteristics is shown in Table 1. The mirrors are mounted in two different wood assemblies, the first with the illuminating source and the second with a sliding tower for focusing. In Figure 1 the two assemblies are positioned face-to-face at the beginning of the experiment.

Figure 1. The two parabolas positioned face-to-face to illustrate the normal incident reflection.

Table 1. Parabolic reflectors characteristics.

Substrate	Aluminum
Diameter (mm)	304.8
Effective Focal length (mm)	76.2
Center hole diameter (mm)	19.0
Coating	Uncoated

The selected light source is an Osram Halolux Ceram® halogen lamp (Figure 2) with the following characteristics:

Table 2. Osram halogen lamp characteristics

Power (W)	205
Luminous flux (lm)	4200
Temperature (K)	3000
Voltage (V)	230 AC
Connector	E27
Dimmable	Yes

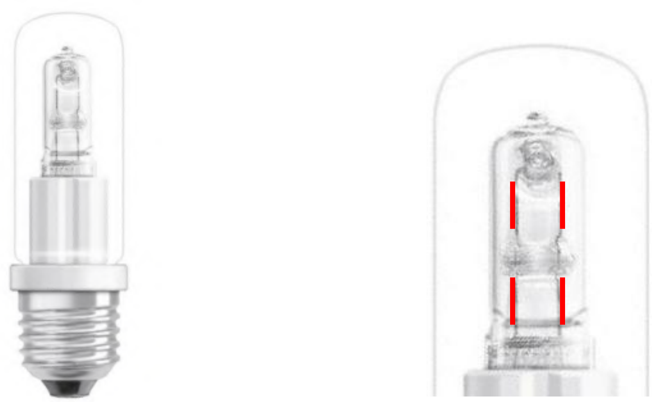

Figure 2. The Osram Halolux lamp and a detail of the four filaments (highlighted in red).

Most of the radiation emitted from a halogen lamp is in the infrared spectrum, much less in the optical region and less than one per cent in the ultraviolet band. If the lamp is manufactured with only the usual quartz capsule, a screen is needed to avoid eye or skin exposure to UV radiation. Normally a simple glass window in enough, as in house appliance, but the Halolux lamps already have an UV filter on the external tube, guaranteed for two years with a typical daily use of 2.7 hours.

The lamp is dimmable with a simple TRIAC circuit, so it is possible to start the experiment with a low light level to illustrate the focusing capacity of the parabolas and then use the full power only during the match lightning. A secondary but useful characteristics of the lamp is the typical arrangement of the four filaments (Figure 2), that can be easily recognized on a screen for focusing purposes; although this reduces the light on the exact focus of the second parabola (the total heating power is not concentrated in a small spot), this is still enough to light a match.

The two parabola experiment is conceived to be easily transportable and dismantled in a plastic box of 40 x 35 x 30 cm^3, as shown in Figure 3.

Figure 3. The two parabolas experiment partially dismantled near its transport box.

2.2 First experiment: a screen in the focal point of the second parabolic mirror

In this first experiment, a screen is positioned at the focal point of the parabolic mirror. Ray-tracing is also used to explain the results. The experiment is meant to show:

1) the image is created at the focal point (Figure 4 experiment, Figure 6-7 ray tracing);
2) the image is inverted (Figure 5 experiment, Figure 8 ray tracing);
3) a black line is absorbing and will start to ignite sooner that the white part of the paper (Video 1).

Figure 4 shows a white paper mounted on the sliding tower in three different positions with respect to the focus length of the second parabola. The first picture on the left illustrates a blurred image because the screen is not in the right position, in this case at a distance greater than the focus length. The second picture shows also a blurred image, but with the screen positioned at a mirror distance smaller than the focus length. The third picture illustrates the screen in the right position, with a good image of the lamp filaments (a sketch of the lamp is printed on the paper as a reference).

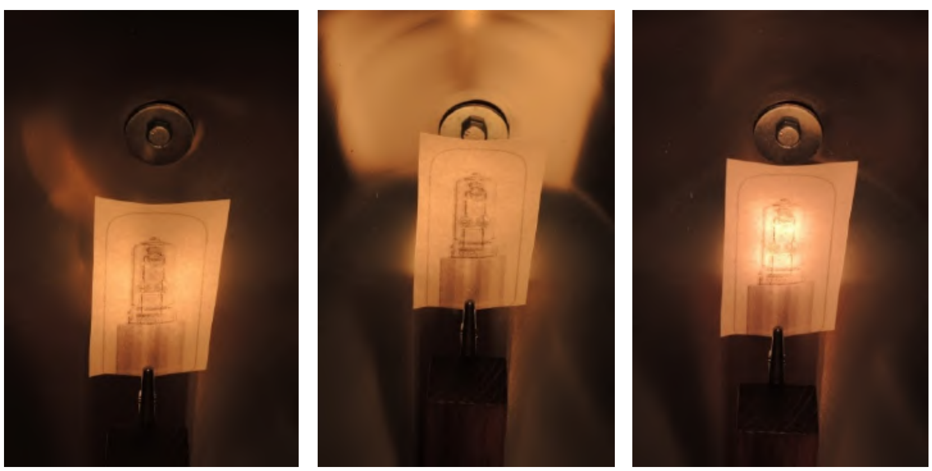

Figure 4. Three positions of the screen in the two parabolas normal incident experiment. From left to right: 1) Screen positioned at a distance greater than the focal length; 2) Screen positioned at a distance less than the focal length; 3) Screen rightly positioned in the focus of second parabola.

The image created on the screen is inverted upside-down, due to reflection; this is shown in Figure 5, where the lower pair of lamp filaments is screened by an aluminum tube.

Figure 5. Left: The aluminum tube is blocking the lower part of the source. Right: the higher part of the source is imaged in the lower part of the screen.

Figures 6, 7, 8 show the result of the ray tracing. In Figure 6, a point source in the focus of the first parabola is imaged in a point at the focus of the second parabola. Figures 7-8 show that, if the source is an extended object, as the lamp of our experiment (Figure 2), the image is inverted and distorted.

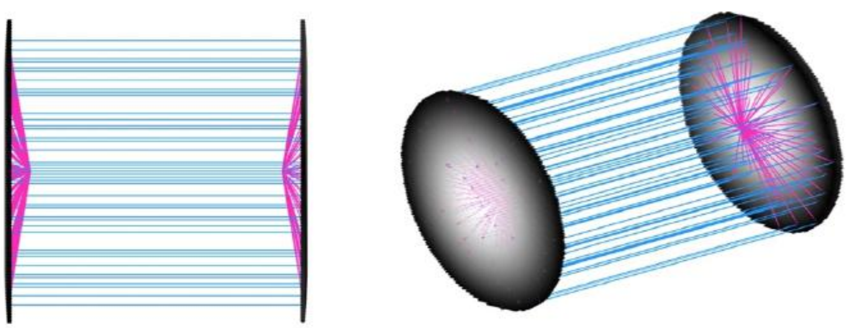

Figure 6. Ray tracing of the two parabolas system for a point-like source in the focus. The result is a point-like image in the focus of the second parabola.

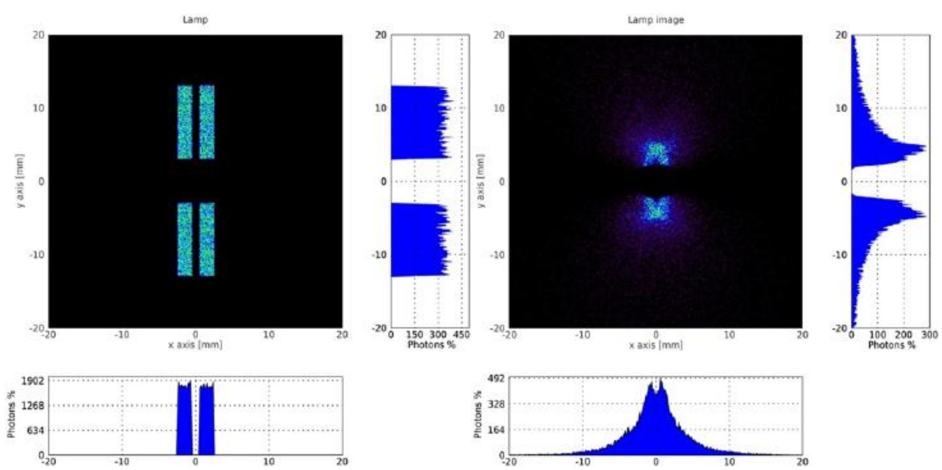

Figure 7. Ray tracing of the two parabolas system for a source as the one used in the experiment (left). The result, at a focal distance corresponding to the parabola focal length, is a distorted image (right).

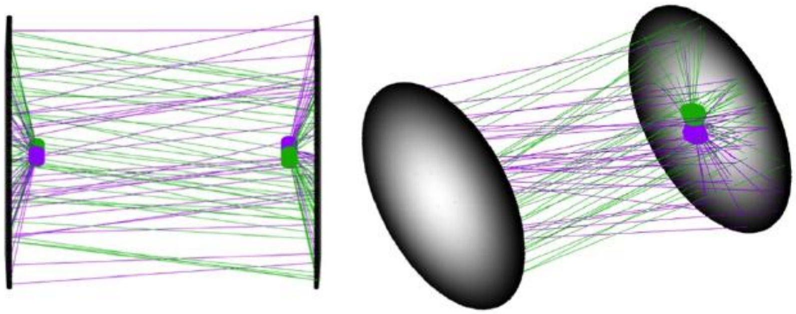

Figure 8. Ray tracing of the two parabolas system for a source as the one used in the experiment. The image is inverted.

Video 1 shows how black objects absorb more heat than white ones; a small sheet of paper with four black lines is positioned in the focus of the second parabola, so the black lines are placed in the low pair filaments image, while the upper part of the paper is completely white. It can be shown, using the lamp at mid power, that only the black lines absorb enough heat to start to burn the paper.

Video 1. The experiment showing the different heat absorption between black and white paper.
http://dx.doi.org/doi.number.goes.here

2.3 Second experiment: a match in the focal point of the second parabolic mirror

When a match is positioned in one of the two light spots created by the filament pairs in the focus of the second parabola, and the power of the lamp is increased, the match itself will light up as shown in Video 2. The match is heated by focused radiation and ignited in about 30 seconds. The video shows also that, when the match is ignited and the lamp is powered off, an inverted image of the fire blob is created on the lamp bulb.

Video 2. The lightning of a match in the two parabolas experiment. http://dx.doi.org/doi.number.goes.here

3 GRAZING INCIDENCE EXPERIMENT WITH VISIBLE LIGHT SOURCES

3.1 Introduction

For X-rays, the refractive index *n* of the material is approximately 1; therefore, to focus X-rays, it is not possible to consider either lenses using refraction, or mirrors using reflection in normal incidence. For this reason, an X-ray focusing optics needs to be reflective and work in grazing incidence.

The first idea for a focusing telescopes was proposed by Giacconi and Rossi in 1960 using a parabolic grazing-incidence surface. Anyway, the parabolic shape is affected by a strong coma aberration. To minimize the coma aberration, the combination of two confocal and coaxial conical surfaces can be used, as already proposed in 1952 by Wolter for X-ray microscopy: in the Wolter I configuration, a paraboloidal surface is followed by an hyperboloidal one. This configuration was then adopted for astronomy by Giacconi and collaborators, considering also the advantage of the double reflection to reduce the focal length by a factor of two, important for optics that have to work in space. If the angular requirement is not stringent, the Wolter I profile can be substituted by a double cone approximation. In *BeppoSAX*, the optics has adopted the double cone approximation for ease of production. It was the first optics produced with the replication technique, developed by Oberto Citterio, where Nickel electroformed mirrors are replicating from a superpolishing mandrel in Aluminum, to limit the costs of the payload[1, 2].

Grazing incidence optics has a small collecting geometrical area, given by the projection of the first section on the aperture plane. To increase it, a number of coaxial and confocal mirrors with decreasing radii (mirror shells) are assembled, with the incidence angle decreasing from the outer to the inner shells. The nesting efficiency is determined, among other factors, by the mirror shell thickness: the thinner the mirror shells, the denser the nesting can be. In *BeppoSAX*, 30 nested shells, with thickness from 0.2 to 0.4 mm, are integrated and aligned in each mirror module.

Table 2 summarize the characteristics of the flight configuration of the SAX optics[3]. They also correspond to the ones of the two demonstration models. The diameters given in Table 2 are considered at the Intersection Plane (IP), which is the plane common to the two cones sections. A schematic view of the SAX optics assemblies is shown in Figure 9[4], where the supporting tube with the alignment spiders is visible.

Table 2. SAX optics characteristics.3

Inner diameter - IP (mm)	66.4
Outer diameter - IP (mm)	158.6
Length (mm)	300
Number of nested mirrors	30
Focal length (cm)	185
Total geometrical collecting area (cm^2)	123.9
Total weight of mirrors (Kg)	8.7
Optical assembly weight (kg)	13.0
Overall weight including stand (kg)	18.6

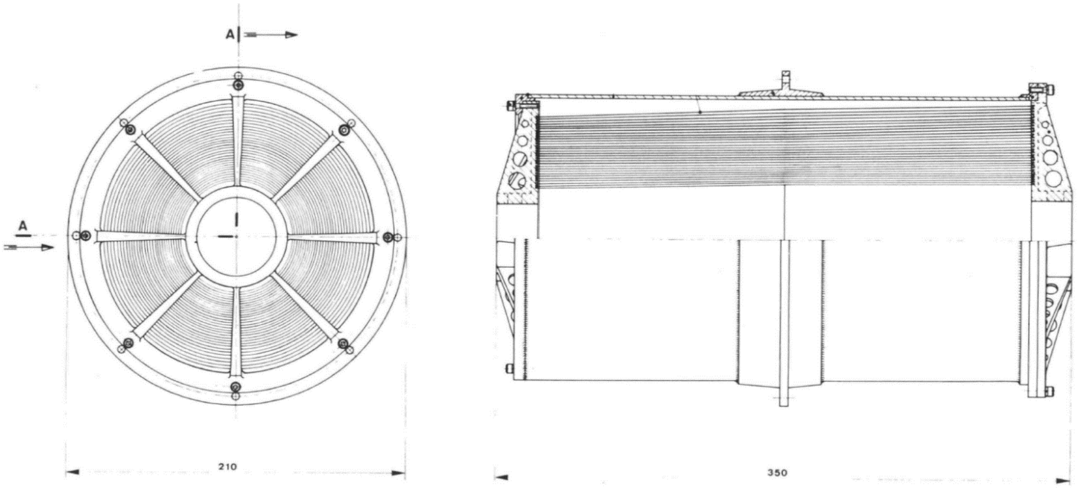

Figure 9. Schematic view of the BeppoSAX grazing mirrors.

During the development of the SAX optics, two Demonstration Models were built and used for tests at various X-ray facilities. The Demonstration Models are now part of the historical exhibitions in Milano at the Brera Observatory (Merate site) and at INAF-IASF Institute (Figure 10). It is therefore possible to use them for outreach, both for students and teachers of secondary schools, and for the public, to explain X-ray reflection using grazing incidence. Unlike the two parabolas experience, in this case the dimensions of the system and the weight of the mirror assembly (18.6 kilograms for the item at IASF Institute) do not allow an easy transportation of the entire experiment, so it can be shown only during visits at Merate or IASF Institute.

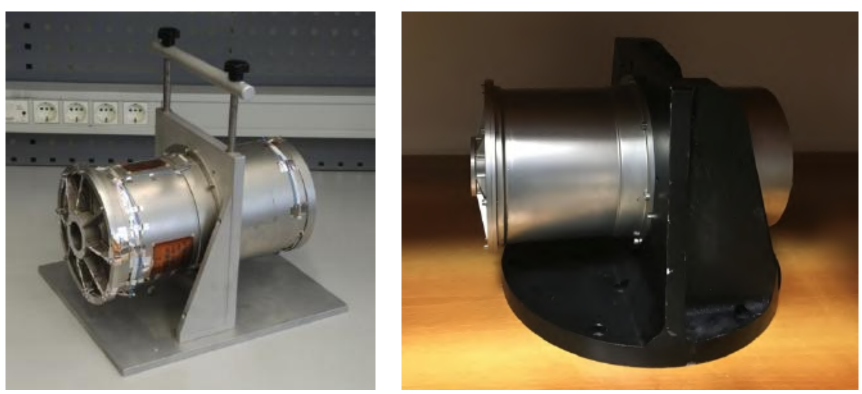

Figure 10. The two mirror demonstration models of BeppoSAX in Milano. Left: the system available at IASF institute; Right: the other mirror assembly at Merate (Brera Observatory).

Since X-rays are ionizing radiations, and not suitable for outreach, visible light sources were considered: two setups were built (see Section 3.2 and 3.3). In order to have a plane wave at the entrance of the mirror assembly, a Fresnel lens from Edmund Optics was procured. This, compared to a parabolic mirror, has the advantage to be cheaper. The selected Fresnel lens has the characteristics shown in Table 3. The focal length (304 mm) is reasonably short to contain the whole setup length. The effective diameter (152.4 mm) is slightly less than the entrance aperture of the grazing mirror assembly (158.6 mm), but still large enough for our purposes.

Table 3. Fresnel lens characteristics

Substrate	Acrylic
Dimensions (mm)	170.2 x 170.2
Effective Focal Length (mm)	304.8
Grove density (grooves/inch)	50
Transmission (%)	92
Wavelength Range (nm)	400-1100

A drawback of the Fresnel lens is the creation of a chromatic aberration, as shown in Figure 11 using a point-like source and without the *BeppoSAX* mirror.

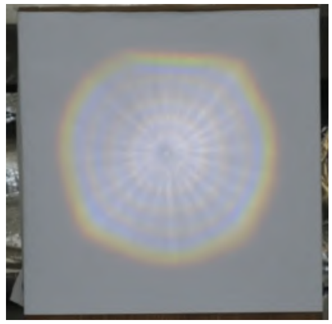

Figure 11. The chromatic aberration of the Fresnel lens.

3.2 Grazing incidence setup A

In the first experiment with the *BeppoSAX* mirrors, the same light source of the previous experiment is used (Osram Halolux lamp). The lens and the lamp are installed on a simple stand realized with mountable bars, to position the lens at the right height and just in front of the grazing mirror entrance; the lamp is positioned at the focal distance from the lens, powered by a TRIAC dimmer circuit as in the two parabola experiment. The screen for the resulting image is positioned at the focal length for the *BeppoSAX* concentrator, i.e. 185 cm from the IP. The entire experiment has a length of about 2.3 meters, as shown in Figure 12.

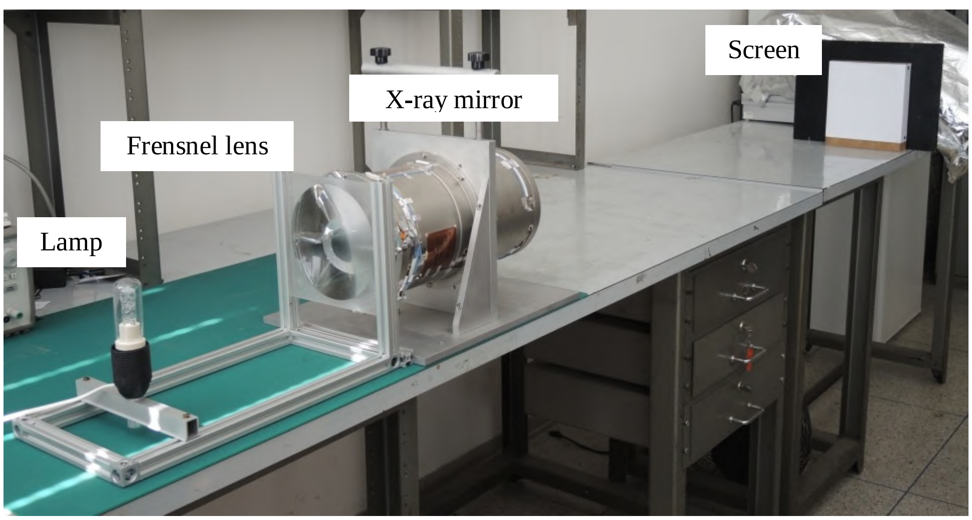

Figure 12. Grazing incidence setup A: Osram Halolux lamp, Fresnel lens, BeppoSAX mirror

The lamp image formed on the screen is shown in Figure 13. The filament image is about six times greater than the dimensions of the real filaments; this can be a question for the students performing the experiment: why is there a magnification of an object positioned at the focal length of a lens? This is due to the dimensions of the object (i.e. the lamp filaments), that is 8 mm x 22 mm (centered on the Fresnel lens focus): in this case, the source is far from being a point source. Great parts of the source will act as off axis sources: the extremes of the filaments are 11 mm off axis, which corresponds to about 2 degrees for a (Fresnel) lens with a focal length of 304 mm. Considering the *BeppoSAX* plate scale of 111.5 arcsec/mm, the extremes of the filaments are imaged at about 67 millimeters off the axis, i.e. about six times the dimensions of the filaments, the magnification factor we observe on the screen.

Figure 13. The lamp image on the screen.

To improve the quality of the image, a source more point-like is needed. To this end the setup B was built.

3.3 Grazing incidence setup B

A 0.6 mm diameter pinhole was created on a thin brass sheet (0.3 mm width), and the pinhole positioned on the optical axis and at the focus of the Fresnel lens. The lamp of setup A (i.e. the one used for pursuing the normal incidence experiments) did not have enough power to create a good image of the pinhole. Therefore a high power LED from ProLight (part no. PK2N-3DNE-BVR7) was procured and positioned just behind the pinhole. Its characteristics are reported in Table 4. This LED is powered by a controlled power supply and it needs a heatsink to maintain its temperature inside the working limits. The brass sheet with the pinhole and the power LED with the heatsink are mounted on a two axis micrometer linear stage to position the pinhole in the focus of the Fresnel lens (Figure 14).

Table 4. 3W Power LED from Prolight characteristics.

Forward Voltage (V)	3.3
Forward Current @ 3.3V (mA)	700
Luminous flux (lm)	199
Aperture angle (degrees)	55
Diameter (mm)	2.8
Color	White
Mounting	SMD

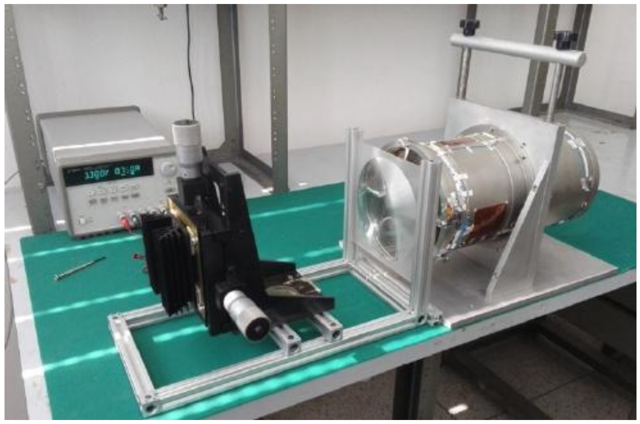

Figure 14. Grazing incidence setup B: Power LED, pinhole, Fresnel lens, BeppoSAX mirror.

The following Sections describe the focusing properties of Setup B with and without the Fresnel lens.

3.3.1 Setup B without the Fresnel lens: source at finite distance

If the Fresnel lens is not used, the rays enter into the SAX optics with large angles. No reflections can occur in shells other the inner one. Table 5 summarizes the characteristic of the inner shell.

Table 5. Inner shell characteristics.[4]

Maximum diameter (mm)	66.746
Medium diameter (mm)	66.387
Minimum diameter (mm)	62.309
Length of each sector (mm)	150

With the source at 510 mm from the IP, the source divergence at the center of the first cone surface is $mean(R_{max}, R_{med})/Dist_{source\_firstcone}$ = 4.4 deg, to be compared to the SAX incidence angle at the inner shell, given by $atan(R_{max}–R_{med})/L$ = 0.26 deg. Since the source divergence is much larger than the SAX incidence angle, no double reflection can be seen.

The source divergence at the center of the second cone is $mean(R_{med}, R_{min})/Dist_{source\_secondcone}$ = 3.2 deg, with an incidence angle, at the second cone of the inner shell, given by $atan(R_{med} –R_{min})/L$ = 0.78 deg.

Since the divergence angles of the beam source are greater than the SAX incidence angles, and the reflected rays will have the same angle of the incidence ones, the rays reflected by the first cone will be focused closer to the SAX optics than the ones reflected by the second one.

Experimentally we see two focal points (Figure 15):

- single reflection on the first cone: focus at 175 mm (Figure 15 left)
- single reflection on the second cone: focus at 510 mm. The focal spot is the central bright image in Figure 15 right. The direct beam from the inner circle and the corona of the spider structure are also visible. The extra focal image of the single reflection on the first cone is also visible.

Figure 15. Focal images without the Fresnel Lens. Left: single reflection from the first cone.
Right: single reflection from the second cone.

Ray tracing (Figure 16) was performed to simulate the experimental images (Figure 15). Only the single reflection from the first cone (green circle in Figure 16 left) is visible in Figure 15 left. Figure 16 right shows the single reflection from the second cone (magenta circle in Figure 16 center), the extra focal image of the single reflection form the first cone (green circle in Figure 16 center), and the direct beam images (light blue circles in Figure 16),

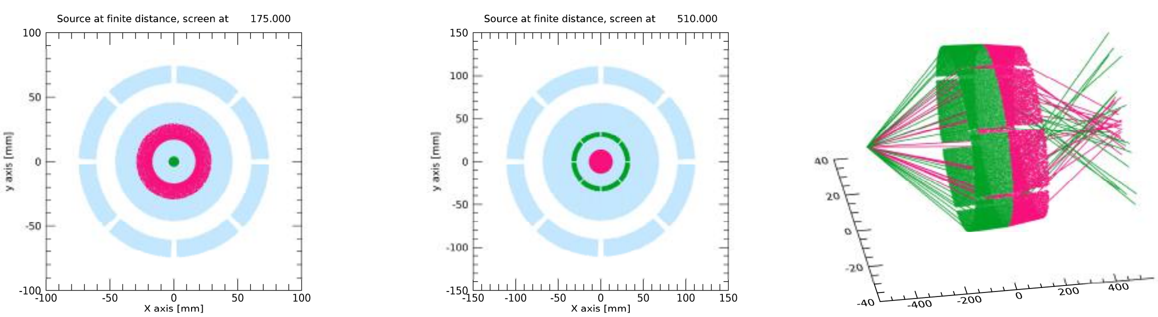

Figure 16. Ray tracing without the Fresnel Lens. Left: single reflection from the first cone. Center: single reflection from the second cone. Right: graphical representation of the rays reflected on the first cone (green) and the second cone (magenta).

3.3.2 Setup B with the Fresnel lens: source at infinite distance

When the Fresnel lens is in place, with the source in its focus, the rays enter into the SAX optics almost parallel and can undergo reflections on all the shells. Single reflections from shell other than the inner one are impossible by design. On the inner shell, only the second cone can have a single reflection image, as the rays reflected by the first cone will undergo double reflection on the second one.

Experimentally we see two focal points (Figure 17):

- single reflection on the second cone of the inner shell: focus at 1260 mm (Figure 17 left)
- double reflection on all shells: focus at 1850 mm (Figure 17 right)

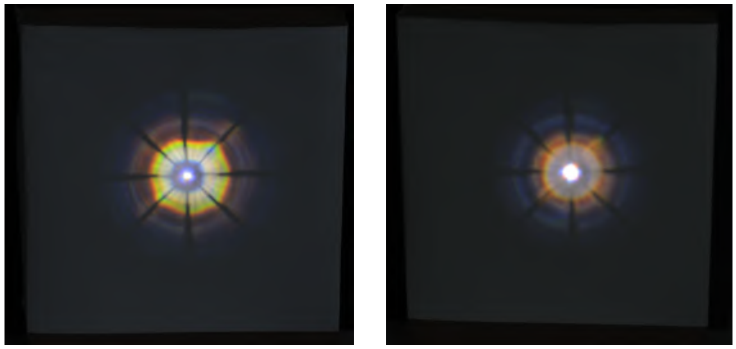

Figure 17. Focal images with the Fresnel Lens. Left: single reflection from the second cone. Right: double reflection.

Ray tracing (Figure 18) was performed also for this case. Figure 18 left shows the focal image of the single reflection on the second cone (magenta circle) and the intrafocal image of the double reflection (blue circle). Figure 18 center shows the focal image of the double reflection (blue circle) and the extrafocal image of the single reflection on the second cone (magenta circle). The direct beam is also shown as in Figure 16.

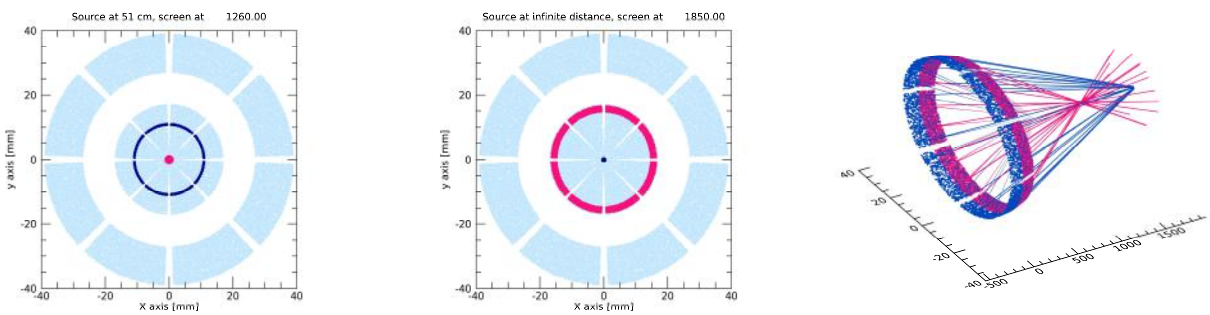

Figure 18. Ray tracing with the Fresnel Lens. Left: single reflection from the second cone. Center: double reflection. Right: graphical representation of the rays reflected on the second cone (magenta) and from both cones (blue)

4 CONCLUSIONS

X-ray optics are using light reflection at grazing incidence to focus X-rays. We challenged ourselves in demonstrating it in an outreach program, making visible the invisible. To this end, we have used a qualification model of the X-ray telescope *BeppoSAX*, in storage at INAF-IASF and INAF-OAB institutes, adopting visible light sources. The program is meant both for students and teachers of secondary schools, and for the public visiting our institutes in the Milano area. The experience will give the possibility to see and work with an X-ray telescope, pioneer in high-energy astrophysics that opened the extra-galactic GRB era.

To our knowledge, this is the first time that X-ray telescopes are used for outreach. A first part of the program is meant at explaining light reflection in normal incidence with two parabolic mirrors; the second part will introduce the double reflection in grazing incidence on the SAX double cone geometry.

From this experience, it can be learnt:

1) geometrical properties of parabolic mirrors
2) image formation
3) light refraction, reflection, absorption
4) different focusing setup for X-rays (grazing) and visible light (normal)

5) aberrations, both geometrical and chromatic
6) different result for source at infinite and at finite distance.

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