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# X-RAY TELESCOPE MIRRORS MADE OF SLUMPED GLASS SHEETS

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## I. INTRODUCTION

For several decades, the field of X-ray astronomy has been playing a major role in understanding the processes in our universe. From binary stars and black holes up to galaxy clusters and dark matter, high energetic events have been observed and analysed using powerful X-ray telescopes like e.g. Rosat, Chandra, and XMM-Newton [1,2,3], giving us detailed and unprecedented views of the high-energy universe.

In November 2013, the theme of "The Hot and Energetic Universe" was rated as of highest importance for future exploration and in June 2014 the ATHENA Advanced Telescope for High Energy Astrophysics was selected by ESA for the second large science mission (L2) in the ESA Cosmic Vision program, with launch foreseen in 2028 [4]. By combining a large X-ray telescope with state-of-the-art scientific instruments, ATHENA will address key questions in astrophysics, including: How and why does ordinary matter assemble into the galaxies and galactic clusters that we see today? How do black holes grow and influence their surroundings?

In order to answer these questions, ATHENA needs a powerful mirror system which exceed the capabilities of current missions, especially in terms of collecting area. However, current technologies have reached the mass limits of the launching rocket, creating the need for more light-weight mirror systems in order to enhance the effective area without increasing the telescope mass. Hence new mirror technologies are being developed which aim for low-weight systems with large collecting areas. Light material like glass can be used, which are shaped to form an X-ray reflecting system via the method of thermal glass slumping.

## II. X-RAY MIRROR DESIGN

The optical design of X-ray reflecting mirrors is significantly different from that of optical mirrors. Due to the high energies of X-rays – typically between 1keV to 100keV, corresponding to a wavelength of 0.1nm to 10nm – only grazing incidence mirrors are able to reflect this type of radiation. Typical are angles below 3°; mostly substantially less depending on the wavelength [5]. This leads to a complete different mirror design than what is usual for optical or infrared telescopes, and by far the most frequently used design are the type Wolter-I nested shells [6].

### *A. Wolter-I nested shells*

The Wolter-I mirror design describes a reflecting optics system for X-rays. It makes use of the effect that under grazing incidence X-rays can be reflected and focussed. However, since the reflected beams are strongly off-axis, a secondary mirror is needed to minimise aberrations, especially coma effects. Using a parabolic segment combined with a hyperbolic one with joint focal point, parallel beams can be focussed effectively and without major aberrations.

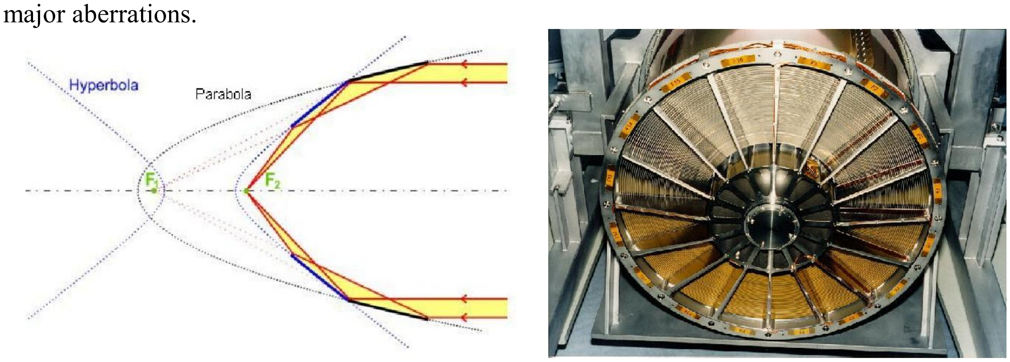


**Fig. 1.** Left: Wolter-I system for reflecting X-ray optics; right: one of the three X-ray telescope mirror modules of the XMM-Newton, launched in 1999. Each mirror module consists of 58 Wolter-I nested shells, designed to optimise the effective area

In Fig. 1, left panel, the principle of Wolter-I optics is shown: parallel beams from a far distant source are being reflected first at the parabolic (black), then the hyperbolic (blue) mirror part, hence performing a double reflection, and are finally focussed at the focal point F2. The yellow zone visualises that only a limited area of radiation, ring-shaped around the optical axis, can be focussed using this set-up. This fact however enables us to nest several shells into each other, so that the collecting area can be greatly enlarged.

Fig. 1, right panel, shows as an example one of three mirror systems of the highly successful ESA telescope mission XMM-Newton, launched in 1999 and scheduled to operate until the end of 2014. Its mirror systems are made of gold-coated nickel shells, which have been produced by electroforming on specially designed and polished mandrels [7]. Each telescope consists of 58 nested Wolter-I shells, in order to achieve the highest possible effective area.

For reaching a large effective area within the diameter and mass limits of the launcher, the shells have to be thin with little spacing between each other, to make most use of the front aperture. In the case of XMM-Newton, these nickel shells are between 0.47mm and 1.07mm thick and add up to a mass of 520 kg. With all other parts like baffles, detectors, structure, electronics and solar panels, the entire observatory has a total mass of 3800 kg. This is getting close to the limits of the launching rocket, meaning that the nickel replication technology will not be able to achieve mirrors with significantly higher effective area without exceeding the capacity of the launcher. To overcome these limits, new technologies using light-weight materials need to be developed for future X-ray missions.

## III. THERMAL SLUMPING OF THIN GLASS

### *A. Segmented mirror modules*

A suitable material, significantly lighter than nickel and already in use in a vast number of reflecting telescopes, is glass. Thin sheets of display glass can be shaped, mounted and integrated to form an entire structure of nested shells. However, the process differs from the integration of complete shells: since the glass sheets can only be produced as segments of the whole shell, the mirror sheets are combined to form single modules, which are subsequently adjusted and integrated to form a petal-based complete telescope system (Fig. 2).

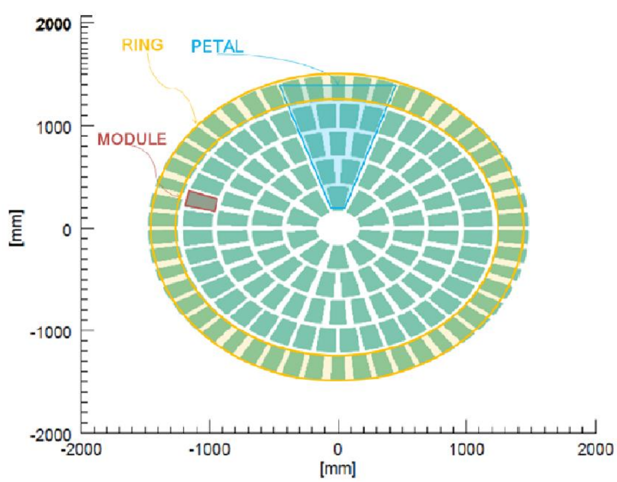


**Fig. 2.** Design of an entire mirror system using an arrangement of modules made of glass segments. Each of these 150 modules holds between 40 and 100 single glass sheets.

Fig. 2 describes a complete telescope system made of slumped glass sheets [8], meeting the requirements for the future X-ray telescope ATHENA which has recently been selected by ESA as the next large mission to be launched in 2028 [4]. The current baseline for ATHENA is the silicon pore optics (SPO) [9], based on thin silicon wafers with an etched structure on one side. The wafers are bonded together to form an approximation of a Wolter-I profile and the radiation travels through the etched spaced, the pores, to the focal plane. Also the SPO needs to produce segments which are subsequently adjusted and integrated to form an entire mirror system. Although the SPO is giving promising results on large radii and long focal lengths, our team at MPE focusses on the hot slumping of thin glass sheets which has been proven e.g. by NuSTAR [10], a NASA X-ray telescope launched in 2012, to be a technology well suited for X-ray telescope missions.

*A. Glass slumping process*

In order to shape the glasses into Wolter-I mirror segments, at MPE we follow the approach of indirect thermal glass slumping. A thin sheet of glass is positioned onto a concave slumping mould and heated up to the annealing point of the glass, causing the thin glass sheet to deform under its own weight and adapt the shape of the mould surface.

In our laboratories we prefer the method of indirect slumping: a concave mould is used and the optical surface of the mirror is the side of the glass that is not in touch with the mould. An advantage of this method is that the micro roughness of the mould does not affect the optical surface and is proven to be damped by almost a factor of 10 by the glass thickness. One could imagine the opposite scenario, and in fact this is being followed by some other groups [10,11]: the direct slumping uses a convex mould and the optical surface is in direct contact with the mould surface. This has the disadvantage that the micro roughness of the mould surface affects directly the optical surface of the mirror glass. However, the indirect slumping has to deal with the thickness variations in the glass [12] which need to be minimised in order to obtain a good quality mirror surface.

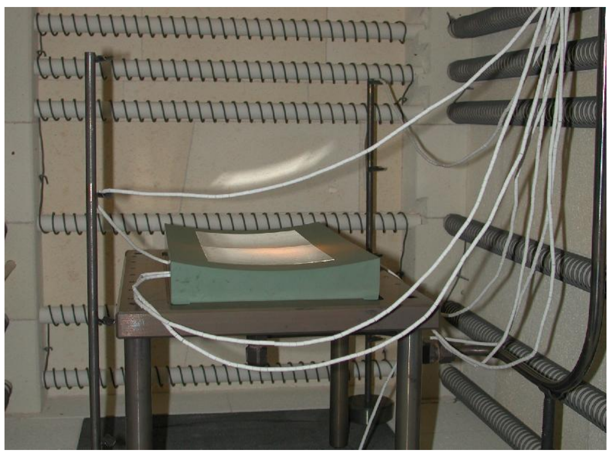

**Fig. 3.** Slumped glass in the MPE lab oven. The intersection line between parabola and hyperbola is clearly visible.

Fig. 3 shows a slumped glass in our lab oven. Clearly visible is the intersection line between parabola and hyperbola, which shows one of the big advantages of the indirect slumping method: the possibility of slumping parabola and hyperbola in one piece. The SPO as well as the groups using direct slumping need to produce parabola and hyperbola separately, leading to extensive adjustments of both parts during integration. Additionally, the kink in the surface gives a much higher stability which is a big advantage for a force-free integration [13].

*B. Material choices for glass and mould*

The choice of material is very important for the quality of the replication and is subject to various challenges. Most importantly the thermal expansion coefficient (CTE) of both materials should match well to avoid tension between glass and mould during cooling. A material well suitable for the slumping process using thin glass sheets is a porous ceramics from Hiper, based on aluminium oxide, which shows a very high thermal stability. The pores are about 6-10µm in size and enable the support of the slumping process using vacuum suction: the mould is positioned on a table with a central hole, which is connected to a vacuum pump. This vacuum support leads evidently to a much better contact of the glass with the mould and avoids air being entrapped between glass and mould due to the concave shape of the mould.

The glass of choice for this porous ceramics is type D263 from Schott, Germany, a down-drawn glass available down to a thickness of less than 150µm which matches the CTE of the ceramics very well and has low initial thickness variations (8-10µm). Several test series have been carried out with this material combination and it has been shown that the replication on this ceramics mould is working very well, down to an error contribution of less than 10% of the contribution of the slumping mould itself [14]. Section VI will give further details on the quality of the slumped glasses as measured at the MPE X-ray facility PANTER. However, due to the porosity of the material, the machinability is limited to values around 60” HEW [15]. Even though the slumping process itself is working well on this ceramics, other mould materials need to be investigated to reach significantly better results for future slumping processes.

Especially CeSiC is a promising material which is already widely used in space applications: it is highly heat-resistant, can be machined and polished to a high quality surface, and its CTE fits well to the glass type AF32 by Schott, also a high quality draw glass. A mould made of CeSiC is available in our laboratories, around a factor of 3 better than the ceramics. Further improvements on the mould are technically possible and not limited by material properties, as was the case for the ceramic material. However, due to the non-porosity of CeSiC, the slumping conditions change, and a new optimisation series is currently carried out in order to make the best use of this material.

## IV. OPTICAL METROLOGY

A vital part in producing high-quality mirror shells is the verification by measurement. Several optical measurement methods are available in our laboratories and are used for measuring mould and glass surface, thickness variations and deformations during integration.

### *A. 3D measurement table*

We have a high-precision 3D measurement table in our cleanroom which is used for the measurement of the surface shape of the mould as well as the glasses. This table is used with a chromatic optical sensor by Precitec with a lateral resolution of 20nm. Using this set-up we obtain a 3D-image of the surface, which can then be fitted to the nominal Wolter-I shape, and the expected X-ray performance of the glass can be estimated.

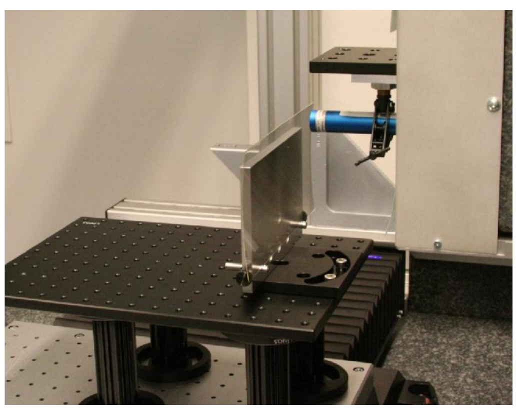

**Fig. 4.** 3D-precision table in MPE clean room with chromatic optical sensor

### *B. Thickness measurement by interferometry*

For measuring the thickness variations in the glass, a very quick and easy method is used: double beam interference using sodium light. The glass is positioned into a box with sodium light reflected to its surface. Since both surfaces of the glass are close enough together, the reflected light from both surfaces overlay and create an interference pattern, which directly displays the thickness profile of the glass [12]. With this method the quality of the glasses can be confirmed, particularly good glasses can be selected, and also glasses polished down to thickness variations of less than 1µm can be verified.

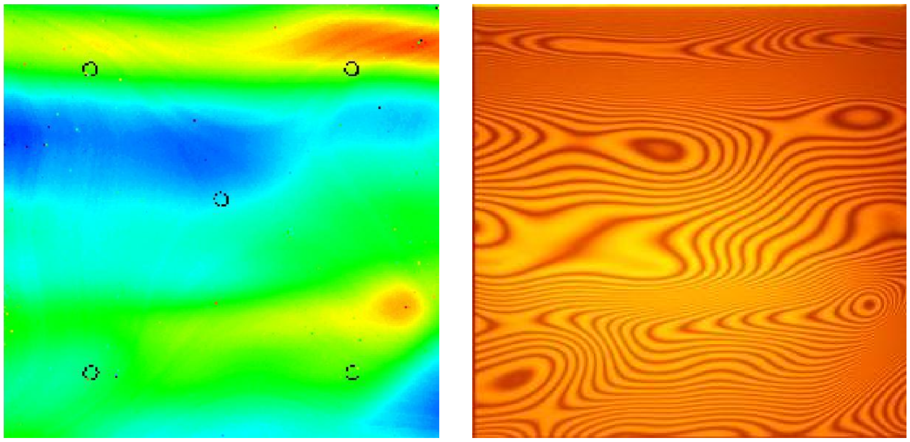

**Fig. 4.** Comparison of glass thickness measured by optical sensor (left) with double beam interference pattern (right) using sodium light. This glass has a peak-to-valley thickness variation of 10µm.

*C. Deflectometer for integration*

An additional optical measurement system has been designed specifically for use during integration. The deflectometer displays a sinusoidal pattern from a screen onto the glass surface, and the reflected wave pattern is being recorded using a camera. From the distortion of the reflected pattern, the angular errors in the surface can be directly deduced and observed in real-time over a chosen period of time. For example the effect of the glue during integration has been proven and quantified, and direct comparisons of the different glue qualities can be carried out with little effort [16].

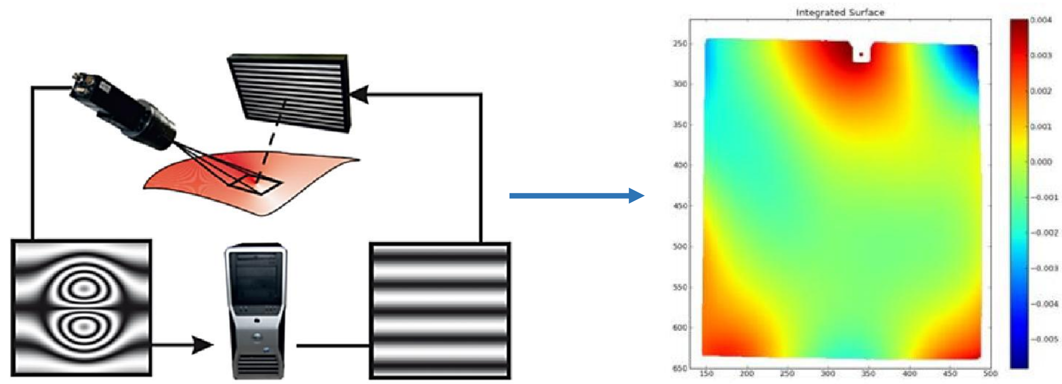


**Fig. 5.** Schematic view of the deflectometer to measure deformations in the glass. The picture on the right is a real measurement of a deformed surface due to glue influence.

## V. INTEGRATION

In recent years we have started investigating the alignment integration of the slumped glasses. For early X-ray tests a simple 1-point mounting was used, which had been improved in recent tests to an 8-point mounting system with a more detailed alignment method using temporary mountings. Latest research is investigating a central mounting at the intersection of parabola and hyperbola with supporting structures along the sides of both mirror parts ([17]; Fig. 6). In parallel a much more improved integration system is being set up, including a hexapod for the alignment and the deflectometer for real-time measurement of the distortion during integration; these are expected to be ready to use before the end of the year. Reference [17] gives further details on the MPE integration set-up.

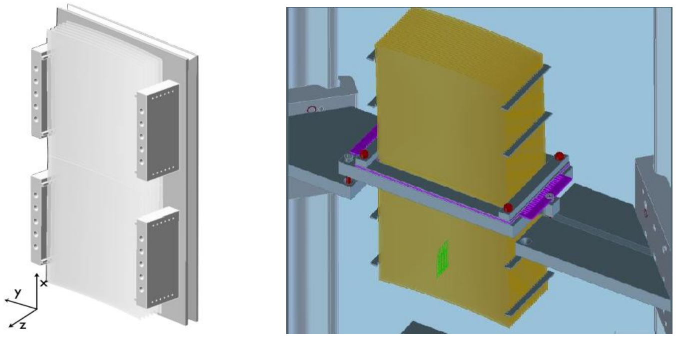

**Fig. 6.** Model of current 8-point mounting system (left) and new central based integration system (right)

## VI. X-RAY TESTS

To verify the quality of the slumped glasses, an X-ray test is being performed at the MPE X-ray test facility PANTER [18]. PANTER has an X-ray source at more than 120m distance to ensure an almost parallel beam, a telescope manipulator where the test mirrors can be mounted, and a detector at up to 12m focal distance.

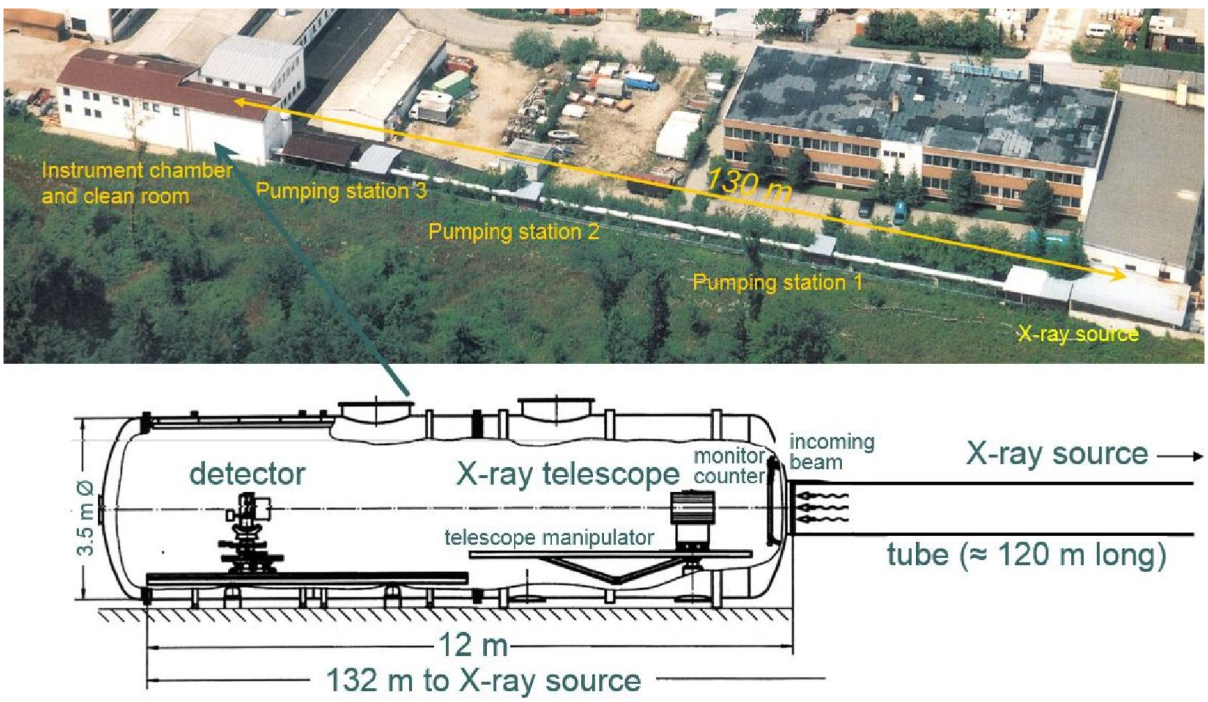


**Fig. 7.** PANTER X-ray testing facility. The lower panel shows a detailed schematic view of the instrument chamber.

| Glass No. | HEW from optical (arcsec) | HEW from X-ray (arcsec) | Mould contribution (arcsec) |
|---|---|---|---|
| CM1-6-48 | 78.6 | **73.0** | 60 |
| CM1-13-40 | 72.9 | **62.1** | 60 |
| CM1-4-52 | 75.8 | **66.1** | 60 |

**Table 1.** Comparison of three slumped glass sheets measured optically and at PANTER. These results show a good reproduction of the mould surface by the glass.

Several glass sheets have been measured at the PANTER X-ray test facility to verify their performance and also the quality of the optical measurements (table 1, [19]). The measurements with the optical sensor are all overestimating the quality of the glasses, and a comparison of the real X-ray performance as measured in PANTER (table 1, bold numbers in third column) with the mould contribution (last column) shows that the glasses replicate the mould quite well and that, given a better mould surface, much better mirror segments could be produced with the glass slumping technology.

## VII. CONCLUSION

The technology of thermal slumping of thin glass sheets has been shown to be a promising method for producing large light-weight mirror systems for future X-ray telescopes. The indirect slumping technology combines several advantages like the combination of parabola and hyperbola in one piece, and the optical surface not being touched by the mould, omitting the need for a highly polished mould surface. We have shown that the mould surface is being replicated very well by the glass and, given a better quality slumping mould, the mirror quality is expected to be substantially better. Research using a new mould made of CeSiC is ongoing, which is a factor of three better than the current ceramics and can be further improved by more processing steps, not limited by the material as was the case for the ceramics.

Several optical measurement methods are available in our laboratories, like a 3D precision measurement table using a chromatic optical sensor, an interferometrical thickness measurement system and a deflectometer for controlling the integration effects. A new integration system including a hexapod and the deflectometer is being set up at the moment, and regular X-ray tests at the MPE X-ray test facility PANTER are being performed to verify the quality of the glass mirrors.

Future tasks include a new slumping series on the mould made of CeSiC, and the research on further improvement of the mould surface in order to reach the ATHENA requirements with the glass slumping technology. Several studies on the feasibility of an X-ray telescope like ATHENA have been carried out, including an industrialisation study [20], which show that the glass slumping technology is a feasible, promising alternative for future large X-ray telescope missions.

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