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From zone plate to microcalorimeter

50 years of cosmic X-ray spectroscopy at SRON

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Abstract. The first method used by the SRON Laboratory for Space Research at Utrecht to spectroscopically image the Sun in X-rays employed Fresnel zone plates. Four Fresnel plates, covering four specific wavelengths, were flown on an Aerobee rocket in 1967 and gave a first useful X-ray image of the Sun in the Si-X line at 51 Å. The technique developed for the solar X-ray images enabled SRON to become the Lead Investigator for the grating spectrographs on several major X-ray satellites, i.e. on the Einstein and EXOSAT satellites, launched in November 1978 and May 1983 respectively, and on the Chandra and XMM-Newton observatories both launched in 1999. Since then, a considerable effort was put into the development of cryogenically cooled, non-dispersive X-ray spectrometers as model payload elements for the XEUS, IXO and Athena mission studies. This paper briefly reviews these developments, highlights some of the resulting scientific insights and offers a few thoughts on the present outlook for a next generation X-ray observatory. The biggest challenge for the realization of such a mission is not primarily technical: global coordination and collaboration, both among scientists and the major space agencies, is a prerequisite for a successful next major leap in this discipline.

Key words. History of X-ray astronomy, Space instrumentation, X-ray spectrographs

1. Introduction

Before discussing the actual developments in high resolution X-ray spectroscopy, that started in the early 1960's at the Laboratory for Space Research in Utrecht, it is perhaps appropriate to point out that this activity was a more or less logical consequence of a strong tradition related to making spectroscopic measurements at the University of Utrecht that dates back to the second half of the 19th century.

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In 1877 the famous Dutch meteorologist Christophorus Buys Ballot, who in 1853 had founded the Sonnenborgh Observatory for meteorology and astronomy, founded a new physics laboratory. This was mainly devoted to the underpinning of physics teaching at the university with state of the art laboratory experiments, in particular those involving optical spectroscopy. Julius, who in 1896 became Buys Ballot's successor as head of the laboratory, built a heliostat spectrograph on the roof of the laboratory in an attempt to measure and to explain the Fraunhofer lines in the solar spectrum. Leonard Ornstein, who took over as director from Julius in 1918, succeeded, together with the innovative and resourceful instrument builder Willem Moll, in establishing very accurate intensity calibrations as a function of wavelength for photographic plates. These calibrations were later on applied by Marcel Minnaert (one of Ornstein's students) for the interpretation of stellar spectra, more specifically for lines in the solar spectrum obtained with the heliostat installed by Julius. For the first time real intensities could be measured for which Minnaert introduced the concept of "the equivalent width" (1923). In Munich, the graduate student Unsöld made a first attempt to link the line strengths of a stellar spectrum to abundances. This lead to the formulation of the concept of the "curve of growth" in 1929 by Minnaert and by Unsöld. In 1931 Antonie Pannekoek, for whom the astronomy institute of the University of Amsterdam had been created, published the first growth curve of a star: α Cygni.

In the 1930s, Minnaert embarked in Utrecht on a very ambitious project: the Utrecht Photometric Atlas of the Solar Spectrum. The observations for this were obtained on some hundred photographic plates at Mount Wilson Observatory in California in 1936. The line strength measurements were published just prior to the Second World War in 1940, after the war the enormous work of converting all the line strengths into solar abundances was started. In the end the major contributor to this analysis was Charlotte Moore of the National Bureau of Standards, the final result was published in 1966 as "The Solar Spectrum", thirty years after the measurements were taken and slightly reminiscent of the long time scales associated with space astronomy projects. Minnaert's student, Kees de Jager, undertook the determination of the temperatures in the solar atmosphere as derived from the spectral lines. The resulting "Utrecht Reference Photosphere" in 1952 would remain a standard for several years to come.

2. X-ray spectroscopy of the Sun in the 1960's

In the early 1960s space research activities were initiated in the Netherlands. The Royal Netherlands Academy of Arts and Sciences, in collaboration with four universities, set up working groups from which the Space Research Organization of the Netherlands (SRON) would eventually emerge in 1983. At Utrecht, in 1961, Kees de Jager started the working group "Space Research of Sun and Stars" and given his background it is not surprising that his first aim was directed towards X-ray spectroscopy of the sun. The first method used in Utrecht to make quasi-monochromatic XUV images of the sun was to use Fresnel zone plates, consisting of a large number of alternating transparent and opaque rings. Completely transparent zones, with a typical width of the outermost rings of 1 μm, necessitates the use of a radial support structure (Figure 1). The first successful trials were made with the aid of electron-optical imaging. The field of view of the available system was however too small for the production of larger ring shaped (or apodised) zone plates with a sufficiently large opaque central section to avoid distortion of the image by zero-order radiation from the sun. The electron optical imaging was therefore later abandoned and replaced by photo-lithography employing

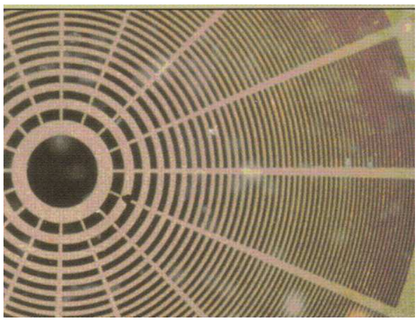

Fig. 1. A non-apodised Fresnel zone plate manufactured in the early 1960s by the Laboratory for Space Research in Utrecht in collaboration with the electron-optics group of the Delft University of Technology.

a holographic method that produced a zone pattern resulting from interference of two coherent spherical wave fronts generated by a beam-split Cd-He laser.

Four Fresnel plates, covering four characteristic wavelengths of He-I, He-II, Fe-XI and Si-X were flown on a sun-stabilized Aerobee sounding rocket in 1967. This produced one useful quasi-monochromatic image of the sun, displayed in Figure 2, in the Si-X emission line at 5.1 nm (Burger and Dijkstra, 1972). Hence, a successful method for the manufacture of short-period (typically microns) transmission grids became established.

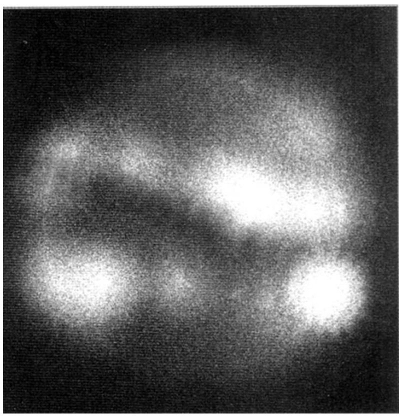

Fig. 2. A quasi-monochromatic image of the Sun taken with a non-apodised zone plate camera in the Si-X emission line at 5.1 nm during an Aerobee sounding rocket flight in 1967.

3. Cosmic x-ray spectroscopy in the 1970/80s: the ANS, Einstein and EXOSAT observatories

The Astronomical Netherlands Satellite (ANS), the first Dutch national satellite, was launched in 1974. This project was a joint venture between Dutch industry and the space research groups in Groningen and Utrecht. The X-ray instruments developed in Utrecht are shown in Figure 3 and comprised among others a parabolic X-ray mirror as a light collector for soft X- rays with a thin window soft X-ray detector, including an associated gas replenishing system, in its focal plane.

The observations with this set of instruments yielded a number of interesting discoveries: for the first time X-rays were detected from a stellar corona (Capella), X-ray flares were detected from cataclysmic variables and Type I X-ray bursts were detected from compact X-ray binaries. Moreover the the soft X-ray collector allowed the spatial mapping of the thermal X-ray distribution of some evolved SNRs by multi-pointing of the 3-axis stabilized satellite over the extended objects. It was clear from this that the optically thin X-ray emission from both stellar coronae and SNRs would constitute a rich field for detailed plasma diagnostics with the aid of high resolution X-ray spectroscopy (e.g. temperatures, densities, abundances etc.). In the meantime, the Utrecht Space Laboratory had also become involved in the US Einstein X-ray observatory (launch 1978). The zone plate experience gained with the holographic method for producing short period gratings could be applied in a straightforward manner to the manufacture of transmission gratings. Inserting these behind a grazing incidence Wolter I X-ray telescope would allow for high resolution spectroscopy of celestial X-ray sources. With the Objective Grating Spectrometer (OGS) of the Einstein observa-

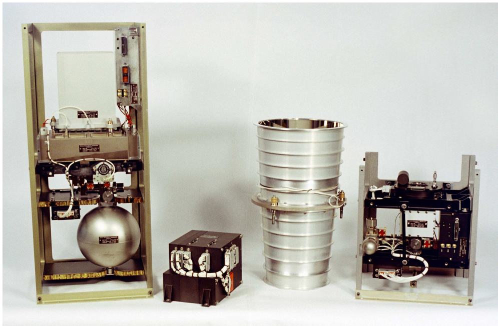

Fig. 3. Elements of the ANS X-ray instrument. Second from right: the grazing incidence parabolic light collector, the spherical gas vessel for replenishment of the soft X- ray focal plane detector (right) is clearly visible.

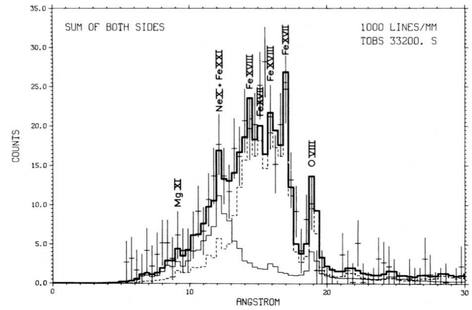

Fig. 4. Einstein OGS spectrum of Capella. Emission lines of a 5 million degree plasma (dashed line) are combined with those of a 10 million degree plasma (thin solid line; from Mewe et al 1982).

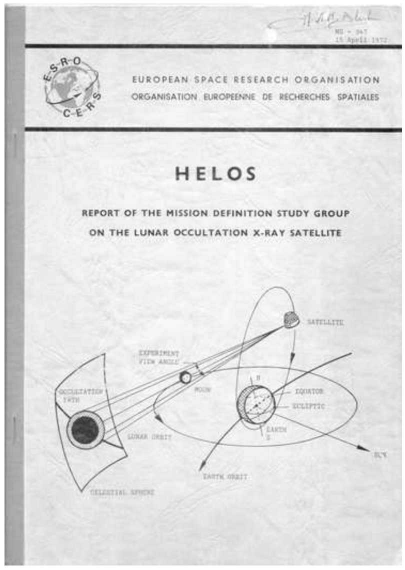

Fig. 5. The HELOS mission study report.

tory, that covered the soft X-ray domain up to wavelengths of a few tens of Å, the first high resolution coronal X-ray spectra were measured. Figure 4 shows the first high resolution spectrum of the Capella corona, discovered by ANS. In 1972, the European Space Research Organisation (ESRO) published an assessment study prepared by a group of European scientists (including author JB) to measure with arcsecond accuracy the positions of celestial X-ray sources by employing the method of lunar occultation: the Highly Eccentric Lunar Occultation Satellite (HELOS). For this purpose the satellite had to be injected in a deep orbit with an apogee of 190000 km and an orbital period of 90 hours. The model payload consisted of an array of collimated proportional counters covering the X-ray energy range of 1 - 50 keV and a number of low energy grazing incidence 'light buckets' of the ANS type. Given the evolution of the X-ray astronomy field during the 1970s and the upcoming launch of an imaging telescope on Einstein, it was decided in 1977 that the focus on the original aim of occultation should be abandoned. The mission with its deep orbit, allowing for long uninterrupted observation times of 76 hours and real time coverage, was to evolve into the first general-purpose European X-ray Observatory (EXOSAT). Given its excellent AOCS system, the light buckets should then be replaced by light-weight X-ray imaging optics. In addition, a gas-scintillation proportional counter, with improved spectral resolution as compared to the proportional counter array, was also incorporated. The Dutch space laboratories played an important role in the development of the Low Energy Telescope: the laboratory in Leiden became responsible for the first development of light-weight X-ray replica optics in space (Beryllium carriers, epoxy separation layers and Gold reflection coatings) and Utrecht took up the development and production of the transmission gratings, again capitalizing on the zone plate and the Einstein experience. The Transmission Grating Spectrometer (TGS, Brinkman et al, 1980) extended much further into the long-wavelength regime than the Einstein OGS, up to wavelengths of several hundreds of Å, including the He-II Ly- edge and line at 304 Å. Both the OGS and the TGS had to be moved into the X-ray beam exiting the X-ray mirror assemblies, and the fear that they would get stuck and not be removable again limited the number of observations conducted with these instruments. The TGS observation of Capella showed, in addition to the OGS data, that the distribution of emission measures (EMs) is not monotonous, they show maxima near 5 and 25 million degrees and a minimum in between (Lemen et al, 1989). The XUV spectrum taken with the TGS

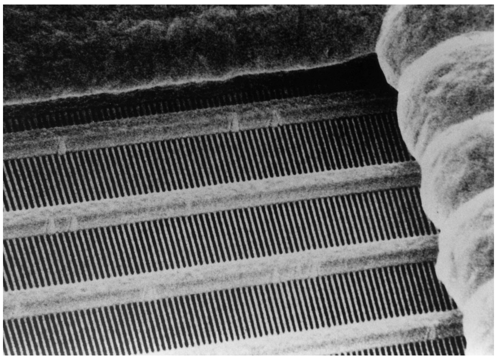

Fig. 6. Electron microscope picture of a grating element for EXOSAT. The many parallel thin bars have a pitch of 1 micron. They are supported by a fine support grid (almost horizontal bars) which, in turn is supported by a much coarser structure (right).

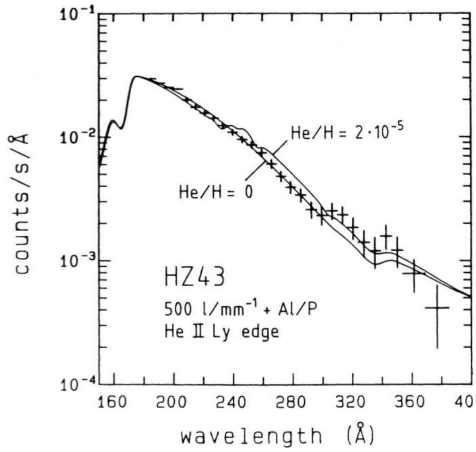

Fig. 7. EXOSAT-TGS spectrum of the hot white dwarf HZ43 yields a stringent upper limit for the He abundance in its photosphere.

of the hot white dwarf HZ43 (Figure 7) enabled a very stringent upper limit to be placed on the Helium abundance (He/H< 2×10^{-5}) in its photosphere, in combination with a much more accurate determination of the interstellar absorption towards this source (Heise et al, 1989). For a proper interpretation of the high resolution X- ray spectra, it was mandatory to develop the topic of theoretical X-spectroscopy at Utrecht. This was started in 1970 by Rolf Mewe, who spent his whole career elaborating the code to compute X-ray spectra of collisionally excited hot plasma's, both for equilibrium and non-equilibrium ionization. Continually extending and improving its scope, he kept track of the improved physical understanding of the processes involved and of the increased capabilities of new generations of computers (Kaastra and Mewe 2005). Subsequent incarnations of these plasma codes, also incorporating photo-ionized plasma's, were worked out in close collaboration with Jelle Kaastra and Duane Liedahl, hence the code is now widely known as the MeKaL code (Mewe et al. 1995). This code forms the basis for the SPEX fitting programme, now extensively utilized in cosmic X-ray spectroscopic observations.

4. Spectrographs on Chandra and on XMM- Newton

Since spectroscopy is the 'queen of astronomy', it is evident that any major X-ray observatory should have a spectrograph. The expertise gained by SRON with the Einstein and EXOSAT observatories, resulted in a role as principal investigator for the Low Energy Transmission Grating (LETG) system on AXAF (after launch renamed Chandra) as well as for the Reflection Grating Spectrograph on XMM-Newton. Nevertheless, the development and production of these large spectrographs required extensive international collaboration, hence both spectrographs are the result of an international team effort.

Regarding the spectrographs on Chandra: to allow for full coverage of the 1-200 Å band, a second spectrograph, the High-Energy Transmission Grating Spectrograph, was incorporated for the short wavelength end. The development and production of this spectrograph was led by MIT as principal investigator. The LETG was designed and built by SRON and MPE-Garching (Brinkman et al, 2000). It comprises grating facets of gold with 1000 lines/mm, supported by a fine and coarse structure with a pitch of 25 μm and 2 mm respectively. The gratings are mounted on a toroidal structure that follows the Rowland circle and are placed directly behind the grazing incidence mirror assembly. With the LETG, the (mainly) iron line complex between 12 and 20 Å can be fully resolved. The spectra taken from stellar coronae provide accurate temperatures from the line ratios of different ions from the same element and density diagnostics from the ratio of the resonance, inter-combination and forbidden lines in the He-like triplets. Figure 9 shows the fully resolved triplets of the He-like ions of O-VII, N-VI and C-V in the corona of Procyon (Ness et al, 2001). The temperatures and densities turn out to be comparable to those of the plasma responsible for the X-ray emission of the Sun. The quality of the observations is now such that the observed spectra can be used to 'calibrate' theoretical line computations.

Fig. 8. Chandra LETG grating facets mounted on a torodal structure upper limit for the He abundance in its photosphere.

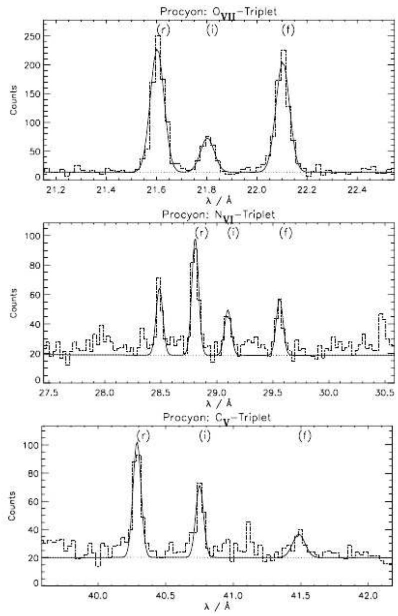

Fig. 9. He-like triplets of O-VII, N-VI and C-V measured with LETG in the Procyon X-ray spectrum.

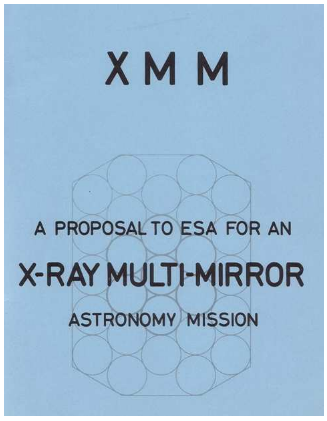

Fig. 10. Cover of the XMM proposal submitted to ESA in November 1982.

The original proposal for XMM-Newton, aiming for a high throughput mission for X-ray astronomy in Europe that could also capitalize on the experience gained with EXOSAT, was submitted to ESA by a group van European X-ray astronomers (including author JB) in 1982. The cover of the proposal symbolized the original presence of 19 telescopes: a cluster of 12 low-energy telescopes (up to 2 keV) and a cluster of 7 high-energy telescopes (up to 10 keV), i.e. a true broad band multi-mirror mission. Obviously the replica technique for light-weight optics production pioneered for EXOSAT was adopted as the enabling technology for this concept. The number of nested shells per telescope was assumed to be around 10 to benefit optimally from repeated use of the high quality mandrels.

Since the number of focal planes had to be reduced dramatically in the final design, the number of shells per telescope went up dramatically (58) to retain the original throughput and to safeguard the required spectral sensitivity (the total number of mirror shells was almost conserved). High-throughput X-ray spectroscopy was adopted as one of the 'cornerstone themes' in ESA's Horizon 2000 long term program, therefore XMM-Newton was already firmly secured as a strategic choice in the ESA science program within 2 years after proposal submission. The optical front end of the Reflection Grating Spectrometer (RGS), the Reflection Grating Assembly (RGA), was built by the University of California at Berkeley and the Lawrence Livermore National Laboratory (den Herder et al, 2001). By virtue of the dispersion at grazing incidence, the effective line density increases as $\rho = \rho_r/\sin\alpha$, with ρ_r the, slightly varying, mechanical ruling density and α the grazing angle. In combination with the 12″ PSFs of the replica telescopes, this still allows for high spectral resolution at high throughput in the range 5 - 35 Å. The

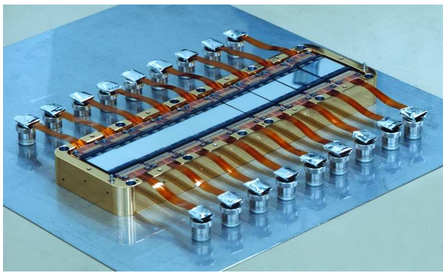

Fig. 11. CCD-strip for RGS spectral read-out developed by SRON.

RGS spectral read-out was designed and built by SRON as PI-institute and includes specially developed low noise, back-illuminated, X-ray CCDs. The CCD chips were custom made and radiation hardened against MeV protons by GEC-E2V (UK). One of the first results of the RGS was the surprising absence of the lines of the cooled gas in several cooling flows in clusters of galaxies: apparently the gas is prevented from cooling below a lower threshold. This is displayed in Figure 12. The RGS also provides powerful diagnostics for assessing the physical properties of the ionized outflows in AGNs. Figure 13 shows a spectral snapshot of the data obtained in a long exposure to Mrk 509. The data exhibit multiple absorption lines from the interstellar medium and from the ionized absorber in Mrk 509. The outflow shows discrete ionization components, spanning four

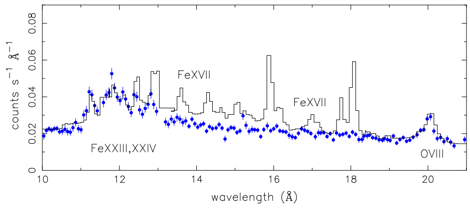

Fig. 12. The RGS spectrum of the cluster of galaxies Sersic 159-03 does not show the expected lines of the coolest part of the cooling flow (Peterson et al., 2001, de Plaa et al., 2006).

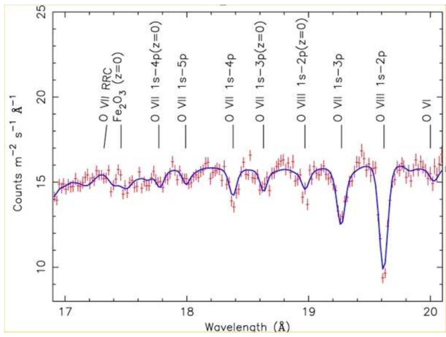

Fig. 13. RGS spectral snapshot of the ionized outflow in the AGN Markarian 509.

orders of magnitude in the ionization parameter ξ. The excellent spectral statistics indicates that the outflow cannot be described by a smooth continuous absorption measure distribution, but shows strong peaks in the range $\log\xi = 1 - 3$ (Detmers et al. 2011).

5. Early 1990s: starting non-dispersive technologies for high-resolution image-resolved X-ray spectroscopy

A major drawback of a wavelength-dispersive technique like gratings for high-resolution X-ray spectroscopy is its limited use for extended diffuse radiation sources, due to a potential mixture of spatial and spectral information. Moreover, in wavelength dispersive devices a substantial part of the incoming beam is lost in the zero-order image. For high resolution X-ray spectroscopy of diffuse hot plasma's in e.g. SNRs, clusters of galaxies or interstellar media, the past two decades have seen substantial research effort in the development of direct detection imaging devices with intrinsically high photon energy resolution. Aiming for the post-Chandra/XMM-Newton era of next generation X-ray observatories, SRON embarked in the early 1990s on this research line as well. The first 5 years were directed towards the investigation of superconducting tunneling junctions (STJs) as suitable X-ray spectrometers. In the end it was concluded that this device held some promise for XUV and optical spectrometry, but was not suitable for main stream X-ray spectroscopy.

Since then SRON pursued a vigorous research programme for the development of X-ray micro-calorimeters employing phase transition thermometers: the Transition Edge Sensor (TES). A TES micro-calorimeter resolution of 3 eV at 6 keV is now routinely obtained by the groups at GSFC/NIST and at SRON. Figure 14 shows a result obtained at SRON for a DC-biased pixel with a Copper photon-absorber. The array sizes to be flown on next generation X-ray missions are limited by the available cooling power, typically a few μW at 50 mK. To enable larger arrays within this constraint, multiplexed read-out of the spectrometer pixels is required. Many types of multiplexers are now under development.

At present Time Domain Multiplexing (TDM), developed by the GSFC/NIST group, has well-proven performance by successfully reading 2x8 pixels in two channels, while maintaining an average energy resolution of 2.93 eV and a distribution of resolution values with a relative standard deviation of 5%. TDM allows for the read-out of a few thousand pixels assuming 16-32 pixels per amplifier chain within the afore mentioned cooling constraint of a few μW at 50 mK in space. On a slightly longer term, Frequency Domain Multiplexing (FDM) and Code Domain Multiplexing (CDM) will mature enough to take over, since both these systems use the available bandwidth more efficiently. As a consequence the read-out of at least 10^4 pixels will become feasible. SRON recently tested an AC-biased TES-matrix by multiplexing 64 spectrometer pixels employing FDM read-out. The average energy resolution obtained for the main Fe-Kα peak was 4.1 eV, not too far from the design goal of 3 eV.

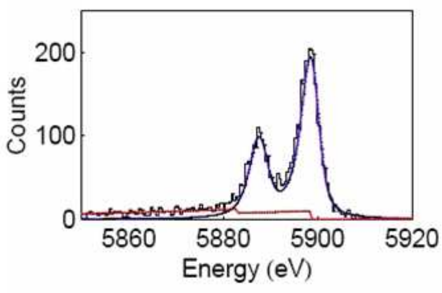

Fig. 14. TES pixel with a Cu-absorber under DC-bias developed by SRON. The energy resolution of the main Fe-Kα peak $dE = 2.5$ eV.

6. High-resolution spectroscopy with the next-generation X-ray observatory

A requirement on large-area X-ray optics of > 5 m^2 at 1 keV and > 1 m^2 at 6 keV for the next major leap in X-ray astronomy is equally driven by the search for super massive black holes at $z > 8$ and by the spectral study of the chemical enrichment history of the Universe. To meet both aims a 5m diameter telescope with a 25m focal length is required. Moreover to avoid source confusion in very deep observations, this telescope should have an angular resolving power of at least 5$''$

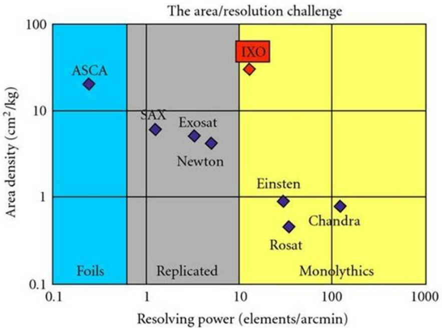

Fig. 15. The effective collecting area per kg of telescope mass, the area-density, as a function of angular resolving power. The value targeted for the next generation X-ray observatory is indicated in red (IXO). The mass indicated is the net mass of the mirror shells. The actual mass, including structure, baffling etc. is at least twice as high.

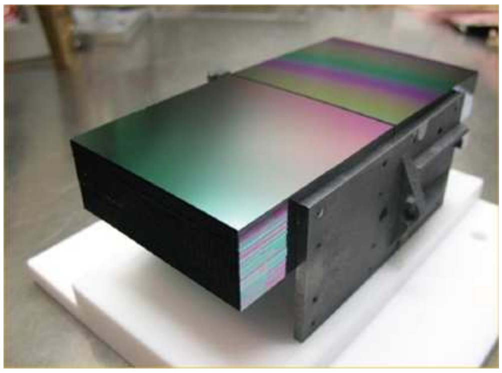

Fig. 16. Prototype mirror module with 45 plates in the first section and 45 plates in the second section. The two modules are permanently glued into a CTE-matched Si-carbide structure to very high accuracy.

with an aim of 2″. Building such a telescope in conventional technology would lead to non-realistic masses that cannot be launched in orbit. Figure 15 shows the effective 'area density' (cm^2/kg) that has been achieved for X-ray telescopes built over the past decades as a function of angular resolving power expressed in resolved elements per arcminute. The area density required for a large X-ray mission for the high red-shifted Universe lies at least one order of magnitude above what has been achieved until now. Presently two technologies are developed for building such a telescope. One is the so-called Si-pore optics under development in European industry funded by ESA, the other is the slumped glass approach pursued at NASA/GSFC and in some European science institutes. At present the Si-pore optics (SPO) is most mature and has been the baseline for IXO and ATHENA. It heavily draws on the availability of large diameter high surface quality Si-wafers and of Si-machining facilities and techniques needed to fabricate ribbed and wedged mirror plates out of these wafers that can be stacked with outstanding surface quality and accuracy. This part of the technology is fully developed to the required quality level and can be fully industrialized for mass production. The real challenge of this technology is stacking of up to 45 of these plates into one module, while preserving the image quality of the underlying mandrel. A prototype mirror module (Figure 16), consisting of 45 plates in the first section (conical approximation of a paraboloid) and 45 plates in the second section (conical approximation to a hyperboloid) was tested in 2010. The measured angular resolution of the prototype module at 3 keV equals 7.8″ for the first four plates in each stack and 16.6″ for the full stack (Bavdaz et al, 2010). Therefore, the most important future development is the improvement of the angular resolution by subsequent improvement of the plate-stacking robot and the enhancement of plate cleanliness prior to stacking. It is to be expected that the 5″ requirement for a next generation mission will be reached within a few years from now including the required technological readiness level (TRL).

7. Lessons learned

Contemplating the history of fifty years involvement in X-ray astronomy projects at SRON the following observations can be made:

- Research and development of innovative enabling technologies (X-ray optics, dispersers, sensors) has been a key success factor.

- The long lead times in space projects introduce substantial tension between R&D and project implementation (TRL).
- Mission level cooperation (coordination) has thus far been regional (NASA, ESA, national).
- Over the past decades, X-ray astronomy has evolved into a well-established branch of main-stream astronomy.
- During the first 50 years, cutting edge X-ray space observatories were relatively abundant, however those days are over!

8. Challenges for the future

- Coping with shrinking budgets due to the severe economic recession in most space-faring countries.
- Dealing with increased competition from other ('new') branches in space astronomy (we are now among the usual suspects).
- Preserving continuity regarding investments in innovative instrument technology, both in terms of scale (throughput, bandwidth) and complexity.
- Dealing with the lack of successful strategic planning and coordination on the global level, both among scientists in the topical discipline and between space agencies (e.g. the dreadful saga of Constellation-X, XEUS, IXO and ATHENA over the past 15 years).

Without any doubt, the last challenge is by far the most prominent one: by failing to line up behind a common goal till now the global X-ray astronomy community has not taken its responsibility!

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