
History of Astronomical X-ray Telescopes in the Czech Republic

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Abstract The design and development of space X-ray telescopes started in former Czechoslovakia in 1969, with the first X-ray telescope flown in 1979. These efforts were part of the former INTERCOSMOS space program, an East European and Soviet equivalent to ESA. 8 space X-ray telescopes were flown on 4 spacecraft and space probes, including the large X-ray telescope on the Soviet Salyut 7 orbital station in 1981. Almost all INTERKOSMOS and soviet spacecrafts with X-ray telescopes onboard used optics of Czech production. We describe briefly the motivation, the history, the performed experiments as well as the designed and developed technologies. After the velvet revolution in 1989 the development of astronomical X-ray optics continued in new conditions, with emphasis on design, developments and tests of various innovative technologies.

Keywords X-ray telescopes · X-ray optics · X-ray astronomy

1 Introduction

The history of the development of astronomical telescopes in the USA, as well as in most of other "western" countries, is usually well known. However astronomical X-ray telescopes had already been designed and developed in the early stages of X-ray astronomy also on the other side of the "iron curtain", in the Eastern block. Most of these developments were carried out in the Czech Republic (formerly Czechoslovakia). These developments have included some specific technologies which are described in this paper.

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2 The early stages

The developments of X-ray optics in the Czech Republic (formerly Czechoslovakia) started in the late 60s and were associated with the early stages of the INTERKOSMOS space program (the East-European analogy to the European Space Agency). It had been decided to focus on the investigation of X-ray emission of our central star, the Sun, including imaging experiments. There was hence a need to design and to develop X-ray lenses for imaging the Sun in X-rays.

The first planning started around 1966 and the first test X-ray mirrors were designed and developed around 1970. The first collaboration team included the Astronomical Institute in Ondřejov, the Optical Development Workshop of this Institute in Turnov (now independent), and the Institute of Gramophone Technology in Lodenice. The development of the first Czech X-ray lenses was initiated by Boris Valnicek and realized under the leadership of Ivan Solc, V. Prazak, and (from 1975) the author of this paper. The first Czech X-ray mirrors were based on grazing-incidence geometry. A Wolter 1 geometry was preferred, in analogy with many other space experiments and telescopes (Hudec et al., 1985). The first Czech X-ray objectives (mirrors) were produced by galvanoplastic replication technology from optically polished glass masters (Hudec et al., 1981). Their apertures were small, between 50 and 80 mm; later on the apertures increased to 120 mm and even to 240 mm. For these larger mirrors, the technology was modified and new collaborators were involved (State Institute of Material Research in Prague and Bechovice, L. Svatek, and J. Urban). The Czech X-ray objectives were flown in space on 4 spacecrafts altogether in 7 experiments. Most of them represented parts of solar X-ray telescopes; one telescope (RT-4M) was dedicated to observations of cosmic X-ray sources (Hudec et al., 1986).

After the political changes in Central and Eastern Europe, and in connection to the closing-down of the INTERKOSMOS program, we focused on developments of innovative X-ray optical systems for space as well as for the laboratory. The innovative space systems developments focused on wide field optics and light mirror shells suitable for future large space telescopes, while the laboratory applications focused on developments of grazing incidence mirrors with extremely small apertures (micromirrors). Some of the studies were carried out in Czech - US collaboration (within the US-Czech Science and Technology Program), others were focused on future collaboration with the European Space Agency ESA.

The design, development, manufacture and tests of X-ray optics have always been an interdisciplinary effort in the Czech Republic. The interdisciplinarity is even growing with new space X-ray telescope projects such as IXO (ESA/NASA/JAXA), since there is a need for a wholly new variety of technologies to be exploited and tested.

The early stages of the X-ray optics developments in the Czech Republic are closely connected to the INTERKOSMOS Space Programme (The Soviet and East European equivalent of ESA, in operation until 1989). All X-ray imaging telescopes onboard Soviet spacecraft were equipped with Czech X-ray optics (exception: X-ray normal incidence mirrors in the special channel of the TEREK telescopes onboard the Fobos and Koronas spacecraft). Later on, laboratory applications also started (Hudec, 1987). In almost all cases, replicated grazing-incidence mirrors of various geometries, types and arrangements have been designed and developed under the leadership (since 1975) of the author of this paper (Hudec, 1987, Hudec et al., 1988). The replication technology in numerous modifications proved to be a powerful tool in solving numerous and varied problems and demands (Hudec et al., 1986).

3 The major milestones

In the following we list the major milestones of the development of the replicated X-ray optics in the Czech Republic.

- 1969 first planning started
- 1970 first X-ray mirror produced (Wolter 1, 50 mm)
- 1971 Wolter 1, 80 mm
- 1976 Wolter 1, 115 mm
- 1979 first mirrors flown in space (two Wolter 1, 50 mm, Vertikal 9 rocket)
- 1980 Vertikal 11 rocket (two Wolter 1, 50 mm)
- 1981 first large Wolter 1 mirror (240 mm)
- 1981 Salyut 7 orbital station, RT- 4M stellar X-ray telescope (Wolter 240 mm, double nested objective)
- 1985 applications for plasma physics, EH 17 mm, PP 20 mm
- 1987 first high quality X-ray foils for foil mirror X-ray telescope (SODART)
- 1988 Fobos 1 Mars probe, TEREK X-Ray solar telescope
- 1989 KORONAS I X-Ray mirror, Wolter 80 mm
- 1990 first micromirror (aperture less than 1 mm)
- 1993 collaboration with SAO, USA, WF X-Ray optics started
- 1996 first Lobster Eye test module produced, Schmidt geometry
- 1997 Lobster Eye Angel geometry project started
- 1999 first Lobster Eye test module produced, Angel geometry

Summary:

- Total number of X-ray mirrors produced: more than 50
- Total number of mirrors flown in space: 8
- Total spacecrafts with Czech X-ray optics: 4
- Total number of space experiments with Czech X-ray optics onboard: 8

4 The replication technologies

The development and manufacture of various types of reflective X-ray optics are heavily affected by manufacturing problems, making their production laborious and hence expensive (Hudec et al., 2000). The most important problems can be summarized as follows: (1) the required microroughness is ≤ 3 nm, in many applications however ≤ 1 nm, (2) X-ray optics is frequently represented by hollow inner surfaces, and (3) there are very strict limits on the slope errors and shape deviations.

4.1 Conventional X-Ray Mirrors

An X-ray mirror can be made of optical glass and/or glass ceramics that is polished to give a very smooth surface (with root-mean-square surface roughness less than 1 nm) and is coated with metal (mostly gold) for better X-ray reflection. Several such reflectors in a cylindrical layout can be nested to give a larger collecting area and thus better sensitivities. These mirrors can be accurately ground to the precise Wolter design and therefore give sharp X-ray images of the order of an arcsecond. Examples

of X-ray telescopes of these types include Einstein, ROSAT, and Chandra. However, due to the thick and massive mirror substrates, these mirrors generally have limited collecting areas, especially at higher energies, since the nesting of shells is limited. These mirrors are also heavy and expensive. This is why most X-ray telescopes use an alternative approach, namely replication, although the conventional classical X-ray mirrors provide the highest angular resolution available. Even the best replication process provides less accurate mirrors than the classical techniques. On the other hand, there are significant requirements for future X-ray optics to provide both high angular resolution and large collecting area (e.g. the IXO project); these efforts will require completely novel technologies to be developed and tested (Inneman et al., 2002).

4.2 The replication alternative

The replication technology represents an important alternative to direct grinding and polishing of the grazing incidence optics. Many of the X-ray mirrors developed in the Czech Republic rely on this technique (e.g. Hudec et al., 1981, Hudec et al., 1984, Hudec and Valnicek, 1986, Hudec et al., 2000). The technology is very advantageous for the production of X-ray mirrors of very small apertures where the direct polishing of small inner cavities is difficult or even impossible, as well as for the production of multiply nested optical mirrors based on numerous thin shells. This technology is usually much more cost effective when compared with classical techniques since from one optically polished master (the most costly part in the whole process) usually numerous identical replicas can be obtained (Hudec et al., 1991).

In general, replication mirrors are suitable for the construction of multiply nested X-ray mirrors with large effective area and moderate angular resolution, while conventional X-ray mirrors are preferable for telescopes with the highest angular resolution but smaller effective area.

4.3 The various replication technologies

The Czech replicated grazing-incidence X-ray mirrors have been produced by various replication technologies (Hudec et al., 1989) listed below:

- 1970 Heavy Replica Technology: heavy electroforming of X-ray mirror shells from polished glass masters, wall thickness 5-10 mm
- 1978 Replica Epoxy Technology tested: epoxy replication of gold evaporated glass masters
- 1980 Replica Epoxy Electroforming Technology: thin electroformed shells reinforced by epoxy
- 1981 as above but carbon fiber filling involved
- 1982 super-thin test Wolter shells for high-throughput telescopes
- 1983 flat master replication: design and development of X-ray reflecting foils for foil X-ray telescopes (SODART, RENTGEN SPEKTR GAMA)
- 1990 first micromirrors (aperture ~ 1 mm) produced
- 1993 first double - sided replicated flats for Lobster telescopes of Schmidt type
- 1998 first replication of Angel geometry Lobster Eye cells

It can be seen that we have developed and tested various modifications of replication techniques, some of them unique (Hudec and Valnicek, 1986, Hudec et al., 2000). The basic modifications include pure heavy galvanoplastic nickel replication, thin galvanoplastic nickel replication, epoxy replication, epoxy/carbon fibre replication, galvanoplastic/epoxy and galvanoplastic/carbon fibre replication. The development has also minimized the internal stresses, allowing multiple replication from one mandrel.

The idea of replica technology is to create a perfect copy of a negative shaped master, with smooth surfaces (Hudec et al., 1989). This is very suitable if it is easier to produce the negative shape.

The two main advantages of replication in X-ray optics design and construction are as follows:

- the production of negative shapes is less laborious (since they represent external and not internal surfaces) and hence less expensive
- the produced shells may be much thinner than is possible with classical technologies (important for light-weight high-throughput nested arrays). With replication technology, the thickness of the mirror-nested shells can be reduced to about 0.2 - 0.3 mm, which is not accessible by classical technologies.

The replication by electroforming (galvanoplastic replication) has been used in the Czech Republic for the development and production of X-ray mirrors since 1967 (Hudec et al., 1981). Since then, the technology has been further developed and modified. A number of modifications exist, meeting different demands (Hudec et al., 1989a, Hudec et al., 2000). The replication is perfectly suitable for the production of X-ray grazing incidence optics since external surfaces can be much easily ground and polished than inner cavities (especially in the case of small apertures). The masters are of high quality optical glass, glass ceramics or metals. It should be noted that the replication technology in X-ray optics is applied by different groups in various modifications (Hudec et al., 1989a).

4.4 Characteristics

The basic characteristics of X-ray mirrors replicated by electroforming can be summarized as follows.

- Reflecting surfaces: electroformed Ni, or electroformed Au, or evaporated/sputtered Au. Other materials are also possible as well as additional coatings.
- External surface structure: metallic (Ni), or CF/epoxy, or sandwich.
- Parameters: the mirrors are polychromatic from as much as 10 keV to optical wavelengths. They have a high reflectivity, up to 90% depending on the wavelength and the grazing angle (e.g. 60% at 0.83 nm and 1 deg incidence angle). The mirrors have smooth surfaces analogous to the surfaces of the masters. The thickness uniformity is of the order of 2% (Hudec et al., 1991). We have exploited the procedures for minimizing the thickness non-homogeneity especially for reflecting foils for foil telescopes (SODART, Hudec et al., 1991).
- Additional technologies: multilayers and/or other additional layers may also be applied to achieve better energy coverage (hard X-rays up to 100 keV). Superpolishing and/or surface quality improvements by lacquer coating are also possible. Especially lacquer coating procedures have been explored in detail, leading to the decrease of surface microroughness.

4.5 Advantages

The replicated X-ray mirrors have numerous advantages which can be summarized as follows.

- A wide variety of possible geometries: Wolter I, II and III systems, conical, ellipsoidal, paraboloidal, flats etc.
- Light-weight and thin shells are possible. This is important for high-throughput X-ray optics (nested arrays with many shells) and for space applications in general.
- Multiple replication of identical elements is possible, minimizing the price of final mirrors.
- There is no need to grind and polish small inner cavities - negative shapes are to be polished
- There are almost no aperture limits including both very small (below 1 mm) and very large (more than 500 mm) apertures. This is important for micromirrors with small hollow cavities (Pina et al., 2000).
- There are many and varied applications possible.
- The surfaces are resistant to the space and/or laboratory environment (cleaning possible, no heat degradation)
- The replicated Au surfaces are smoother than evaporated surfaces.

4.6 Replicated astronomical grazing incidence mirrors

More than 100 X-ray mirrors have been designed, developed, and produced between 1970 and 2004 in the Czech Republic as well as numerous test mirrors for technology purposes:

- Wolter 1 mirrors for space applications, apertures 40 to 240 m (Hudec and Valnicek, 1984). They have been used onboard satellites as imaging elements in X-ray solar and stellar telescopes (Hudec et al., 1986).
- Bent foil mirrors/flats foils. X-ray reflecting foils produced from flat glass masters with sizes up to 300 x 400 mm (Hudec et al., 1991). Thickness homogeneity is better than 2%. Wide range of foil thickness from a few microns up to 1 mm. Designed for the SODART foil X-ray telescope and analogous projects.
- Lobster-eye wide-field X-ray optics, Schmidt geometry, various modules; size of the flats e.g. 80 x 100 mm, 300 x 300 mm, and 23 x 23 mm (Hudec et al., 2003a,b).
- Lobster-eye wide-field X-ray optics, Angel geometry, various test modules; a/L (aperture/length) ratios of about 50-80 (Hudec et al., 2004).

4.7 Replicated laboratory grazing incidence mirrors

The replication technology originally developed and used for astronomical X-ray mirrors has also been used in numerous ground-based and laboratory applications which are listed below.

- PP (paraboloid-paraboloid) microscopes, aperture 20 mm (Hudec, 1987). Collaboration with Lebedev Physical Institute, Moscow, USSR (imaging of hot laser induced plasmas).

- EH (ellipsoid-hyperboloid) Wolter microscopes, aperture 17 mm (Hudec et al., 1987). Collaboration with the Institute of Plasma Physics and Laser Microsynthesis, Warsaw, Poland (imaging of hot laser induced plasmas).
- Conical, ellipsoidal, paraboloidal mirrors.
- Micromirrors with conical, ellipsoidal, and paraboloidal profiles (Pina et al., 2000).
- Foils including those for foil X-ray telescopes (Hudec et al., 1991). Collaboration with Danish Space Research Institute, Copenhagen, Denmark. The main goal was to develop and to test improved high-quality X-ray reflecting foils for the Danish-Soviet X-ray telescope SODART for the satellite mission RENTGEN-SPEKTR-GAMMA.
- Flat and bent mirrors (Hudec et al., 1991). Collaboration with Danish Space Research Institute, Copenhagen, Denmark. The main goal was to develop and to test improved high quality X-ray reflecting foils for the Danish-Soviet X-ray telescope SODART.

5 Conclusion

Numerous X-ray optical imaging elements have been designed and constructed in the Czech Republic over the last 40 years. Various technologies, mostly based on replication techniques, have been explored, some of them still of interest even recently.

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Fig. 1 Various replicated grazing-incidence X-ray mirrors, both astronomical and laboratory, around 1990. These represent various technologies including several modifications of carbon-fibre technology



Fig. 2 The four mandrels used for the manufacture of the X-ray mirror nested array for the RT-4M soft X-ray telescope (Glass ceramics Sital). Flown onboard the space station Salyut 7. (left). Two identical mirrors (large hyperbolas) of the RT-4M mirror array (Ni surfaces). (right).



Fig. 3 Astronomical replicated Wolter mirrors for the KORONAS satellite (replicated from one and the same mandrel). Wolter 1, aperture 80 mm, electroformed nickel (single layer). The mount structures were created during the galvanoplastic process in order to improve the mechanical stability and overall stiffness (unique solution). This was the last INTERCOSMOS program X-ray telescope with our participation.

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