Invited Paper

Imaging characteristics of the Development Model of the JET-X X-ray telescope.

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ABSTRACT

The Joint European X-Ray Telescope, JET-X, is one of the core instruments of the scientific payload of the USSR SPECTRUM-X astrophysics mission due for launch in 1994.

JET-X is designed to study the emission from x-ray sources in the band of 0.3 - 10 KeV; particularly to meet primary scientific goals in cosmology and extragalactic astronomy.

JET-X consists of two identical, coaligned x-ray imaging telescopes, each with a spatial resolution of 30 arcsecond or better. Focal plane imaging is provided by a cooled x-ray sensitive CCD detector which will combine high spatial resolution with good spectral resolution, with particular emphasis on high sensitivity and spectral resolution around the 7 KeV Fe-line complex.

Each telescope is composed of a nested array of 12 mirrors with an aperture of 0.3 m. and focal length of 3.5 m.; the total effective area is 360 cm^2 at 1.5 KeV and 140 cm^2 at 8 KeV.

The mirror shells have a Wolter I geometry and are manufactured by an electroforming replica process.

In order to verify the angular resolution and the imaging capabilities achievable with the proposed manufacturing process a development model of the JET-X optics which is composed by the mirror shell N°3 (ϕ = 278 mm) has been built.

The development model has been tested at the PANTER X-RAY Facility of the Max Planck Institute. The results are reported and discussed in the paper.

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1.INTRODUCTION

The Joint European X-ray Telescope, JET-X, [1] is designed to study the emission from X-ray sources in the band 0.3 - 10 KeV and constitutes one of the core instruments of the scientific payload of the USSR SPECTRUM-X astrophysics mission due for launch in 1994.

JET-X is being developed by a consortium from UK groups (University of Leicester and Birmingham, the Rutherford Appleton Laboratory, the Mullard Space Science Laboratory) Italian groups (Astronomical Observatory of Brera, CNR Institutes in Milano and Palermo, University groups in Milano and Rome), the Max Planck Institute for Extraterrestrial Physics in Garching, West Germany and the Space Department of ESTEC, ESA.

JET-X consists of two identical, coaligned X-ray imaging telescopes, each with a spatial resolution of 30 arcsec HEW (Half Energy Width) or better. The focal plane imaging is provided by a cooled X-ray sensitive CCD detectors which will combine high spatial resolution with good spectral resolution, with particular emphasis on high sensitivity and spectral resolution around the 7 KeV Fe-line complex.

An optical monitor [2] with sensitivity down to m_v=21 is mounted coaligned with the X-ray telescopes to permit simultaneous observation and identification of the optical counterparts of X-ray target sources.

The primary objectives of JET-X are:

1) Imaging with $\leq$ 30 arcsec resolution with a limiting sensitivity at 1 KeV of $\sim$0.5 nJy.
2) Medium resolution spectroscopy ($E/\Delta E \geq 10$) in the 1-10 KeV band with emphasis on high sensitivity and spectral resolution ($E/\Delta E \geq 50$) around the 7 KeV Fe-line complex.
3) Time variability of X-ray spectra on timescale ranging from milliseconds to months.
4) Simultaneous and continuous optical monitoring of the X-ray sources to a limiting magnitude of m_v=21.

The sensitivity required by the scientific objectives of JET-X, implies an effective area of $\sim$350 cm^2 at 1.5 KeV and $\sim$150 cm^2 at 8 KeV. To achieve these effective areas within the dimensions allowed to the JET-X payload, two identical telescopes, each consisting of 12 nested coaxial and confocal mirrors, will be mounted.

To manufacture the X-ray mirrors, a replica technique by electroforming the mirrors from mandrels has been chosen. This technique has already been successfully used for the construction of the X-ray optics of the SAX imaging concentrators[3,4] . For JET-X, two modifications to the SAX optics design have been introduced in order to achieve the more stringent requirement of 30 arcsec HEW for the angular resolution (for SAX the HEW is $\lesssim$ 2 arcmin):

1) the double cone approximation of SAX is replaced by the Wolter I configuration.
2) JET-X mirrors are thicker than the SAX ones in order to achieve a better stiffness.

With the electroforming replica technique, an aluminium mandrel coated with a layer of electroless nickel is machined to the required paraboloid-hyperboloid figure and then superpolished to a surface finish of 0.7 nm RMS. A gold layer is deposited by evaporation under vacuum onto the mandrel surface, and the desired thickness of nickel is then electrodeposited on top of this.

Because the thermal expansion coefficient of the aluminium is about twice that of the nickel, the electroformed mirror is easily separated from the mandrel by cooling it.

The gold is used for two reasons:

1) it has a good reflectivity coefficient for the JET-X energy range,
2) it behaves as release agent because the adhesion of the evaporated gold to the nickel of the mandrel is poor, while the adhesion of the electrodeposited nickel to the gold is very good.

Under normal operation several mirrors can be replicated from one mandrel without degrading it.

In order to verify the angular resolution and the imaging capabilities achievable with the proposed manufacturing process a development model of the JET-X optics which is composed by the mirror shell N° 3 (ϕ = 278 mm) has been built and has been tested at the PANTER X-ray facility of the Max Planck Institute.

The results of these tests, together with the description of the X-ray optical system, are reported and discussed in the following.

2. X-RAY OPTICAL SYSTEM

The X-ray optical system of JET-X is composed of 12 nested, coaxial and confocal mirrors each having a Wolter I geometry.

As mentioned above the construction technique is based on a nickel electroforming replica from superpolished aluminium mandrels coated with a layer of electroless nickel (kanigen).

The thickness of the shells varies from 0.7 mm for the innermost to 1.1 mm for the outermost shell. The thickness of each shell has been determined by Finite Element calculation in order to present a resonant frequency $\geqslant$ 200 Hz and an acceptable image degradation under gravity effects when the telescope undergoes X-ray test on ground with the optical axis in horizontal position. Moreover, each mirror shell must have sufficient stiffness to limit possible deformation during the integration into the mirror mount.

Fig. 1 shows the design of the mirror mounting system which is composed of two front end spiders each having 12 spokes that are supported by a tube which holds in its central zone, the flange for the interface to the JET-X mirror bulkhead.

Precise grooves machined on the spiders spokes provide the support and the optical alignement of the nested mirrors.

The two front ends spiders and the supporting tubes are made of stainless steel in order to match as much as possible the thermal expansion coefficient of the nickel mirror shell.

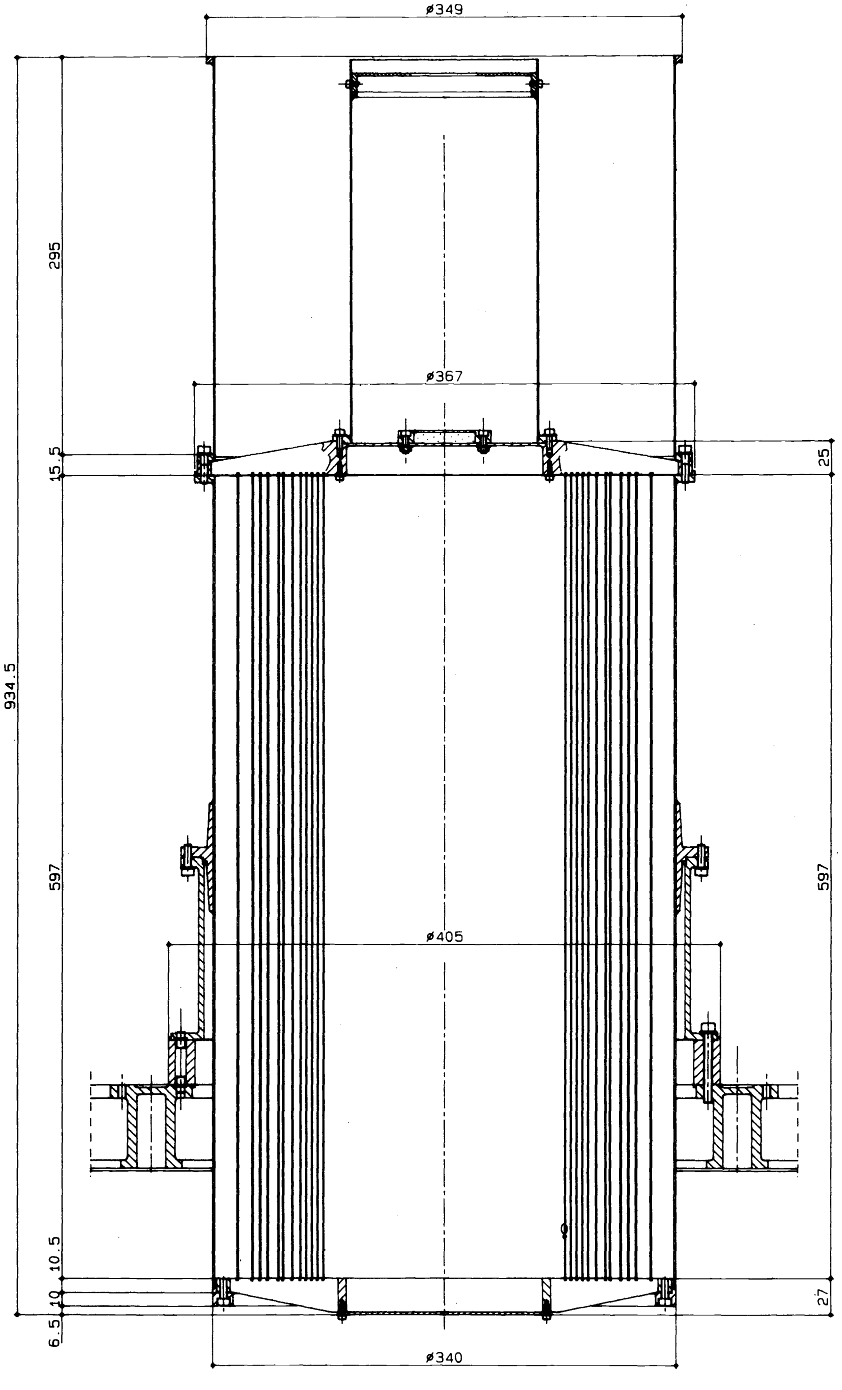

Fig. 1 - Assembly drawing of JET-X X-Ray optics

The mirror parameters are summarized in Table 1.

Outer mirror diameter	300 mm
Inner mirror diameter	190 mm
Mirrors length	2X300 mm
Focal length	3500 mm
Shells thickness	0.7-1.1 mm
Number of shells	12 mm
Reflecting surface	gold
Surface finish (microroughness)	$\lesssim$ 0.7 nm
Configuration	Wolter I
Angular resolution	10-30 arcsec (HEW)
Field of view	20 arcmin (50% vignetting)

Table 1 - Mirror characteristics

Fig. 2 shows the effective collecting area for the two telescopes over the energy ranges on axis and at off-axis angles of 7.5, 15 and 22 arcmin.

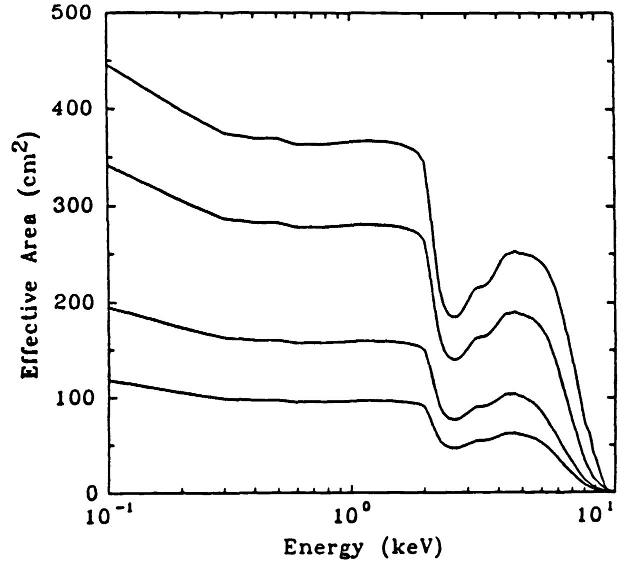

Figure 2. - Total Collecting Area of two JET-X telescopes on-axis, and at off-axis angles of 7.5, 15.0 and 22.0 arc-minutes.

3. X-RAY TEST

The X-ray test of the development model of JET-X optics which is composed by the mirror shell N°3 (ϕ=278 mm) was tested at the Panter facility[5] of Max Planck Institute in Munich.

Fig. 3 shows the development model (D.M.). At the Panter facility the D.M. was mounted on an optical bench which operates in vacuum and can be horizontally and vertically tilted with respect to the X-ray beam.

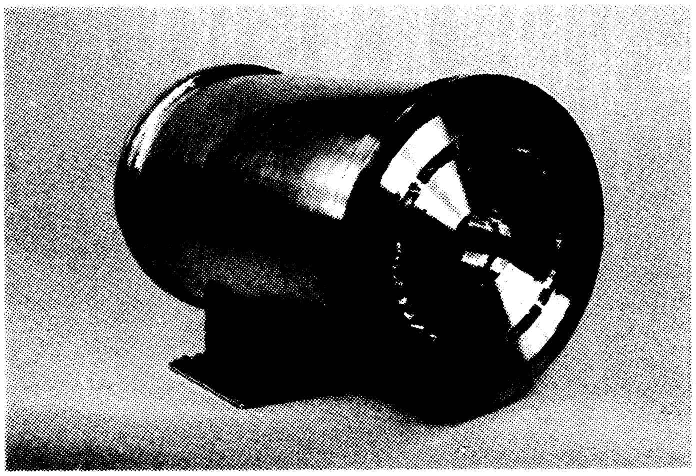

Fig. 3. - JET-X Development Model.

Three types of detector were used:

1) an imaging microchannel plate detector (MCP) having a spatial resolution of 80 micron that, with the JET-X focal length of 3.5 m, corresponds to an angular resolution of 4.7 arcsec.
2) a proportional counter having a 100 micron wide slit.
3) a proportional counter with a sensitive area of ϕ=30 mm. This detector was used for reflectivity measurements.

The detectors can be horizontally and vertically translated and also moved along the optical axis to find the best focus position.

A proportional monitor counter is also mounted in the beam to monitor possible fluctuations of the intensity of the beam during the reflectivity measurements.

The full useful aperture of the mirror is illuminated by an X-ray beam coming from a pointlike source 130 m away. The resultant divergence of the beam is 7.3 arcmin. The results that follow were corrected to bring the source to infinity.

The measurements were made at 0.27; 0.9; 1.5; 4.5; 5.4 and 8 KeV.

The imaging properties of the mirror were determined by making scans across the image at the focal plane and by deconvolving the slit scans in order to derive the encircled power function assuming a circular simmetry of the images. This assumption was considered acceptable by looking to the image quality obtained with the bidimensional MCP detector. The reflectivity was determined with the proportional counter by measuring the beam reflected by the mirror at the focal plane and comparing this measurements with that of the direct beam, introducing the appropriate geometrical factors and the normalization to the monitor counter.

4. RESULTS

Fig. 4, 5 and 6 show the slit scan measurements of JET-X D.M. respectively at 1.5; 5.4 and 8.0 KeV.

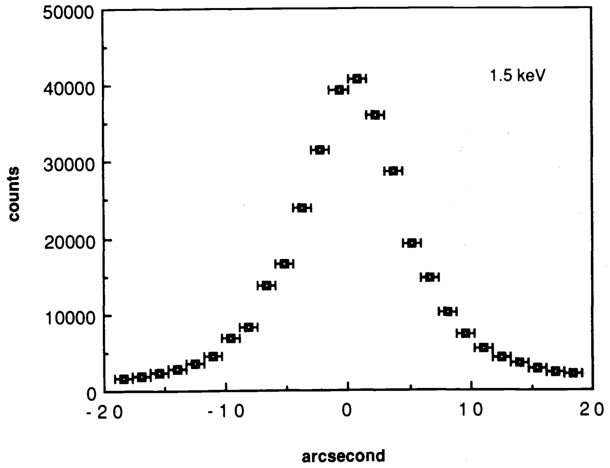

Fig. 4.- Slit scan at 1.5 KeV

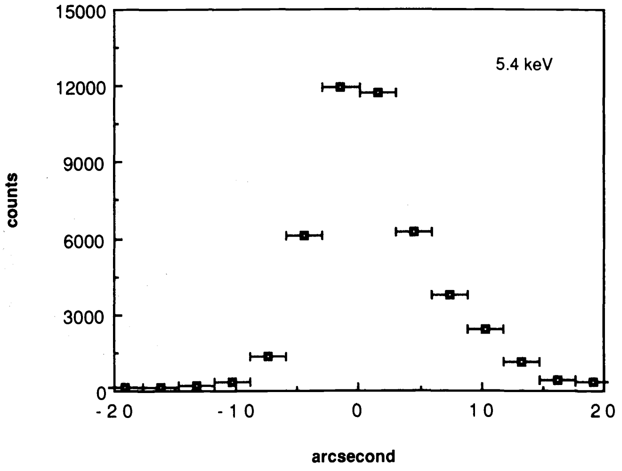

Fig. 5. - Slit scan at 5.4 KeV

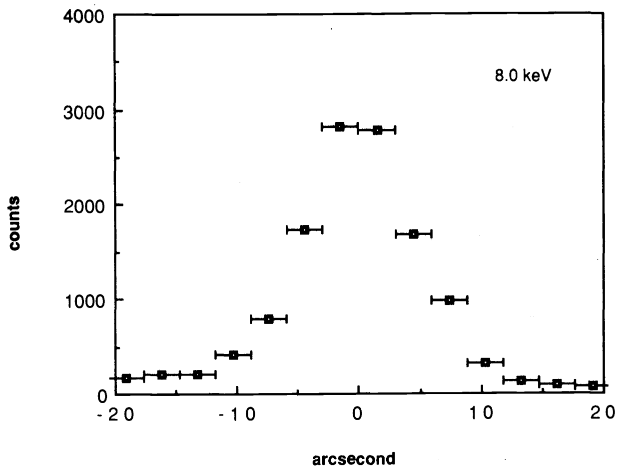

Fig.6.- Slit scan at 8.0 KeV

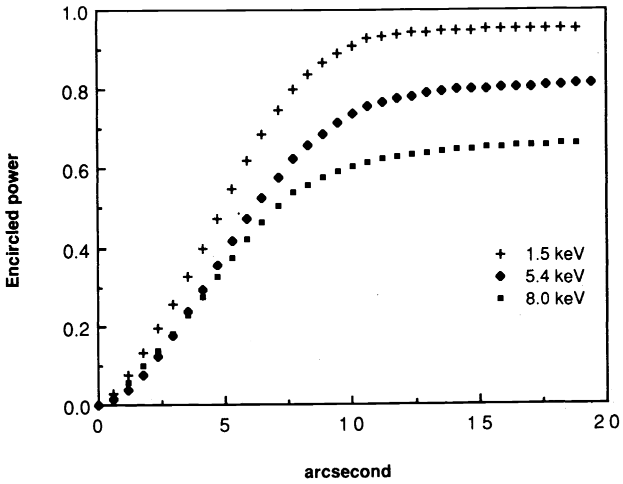

Fig. 7 - Encircled Power Functions derived from slit scans (x-axis = radius)

Fig. 7 shows the encircled power function obtained by deconvolving the slit scan measurements. From these curves an Half Power Radius (HPR) of 5.0; 6.3 and 7.2 is derived for JET-X D.M. respectively at 1.5; 5.4 and 8.0 KeV. The difference in the saturation values in figure 7 is due to the scattering by microroughness which is, well known, increasing with energy; the analysis of the scattered intensity fraction indicates a value of the microroughness lower than 7.5 Å at 8 KeV in agreement with the expected performances.
Fig. 8 shows the simulation of two equal intensity sources at 0.9 KeV separated by 25.6 arcsec realized by taking two equal time exposure with the MCP detector translated of a quantity corresponding to 25.6 arcsec.

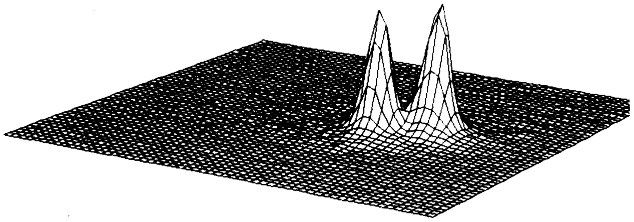

Fig. 8 - Development Model of JET-X. Two equal intensity sources separated by 25.6 arcsec at 0.9 KeV.

During the reflectivity measurements it was noted an unexpected loss of effective area at 0.24 and 0.9 KeV. Assuming a possible contamination from hydrocarbons, the D.M. was exposed to a flash of UV light for one hour.
A tubular lamp was placed in the central region of the mirror. The flashing with UV light is intended to transform non volatile hydrocarbons into volatile ones by the action of the ozone produced by the UV light. The repeated reflectivity measurements indicated an increase of about 10% in effective area with respect to the values obtained before the UV cleaning.
Fig. 9 and 10 show the effective area measurements of the D.M. on axis and 10 arcmin out of axis taken at different energies after the UV cleaning. The measured values of the effective area are compared with the expected ones (dotted line), showing that the mirror reflectivity is at the nominal value.

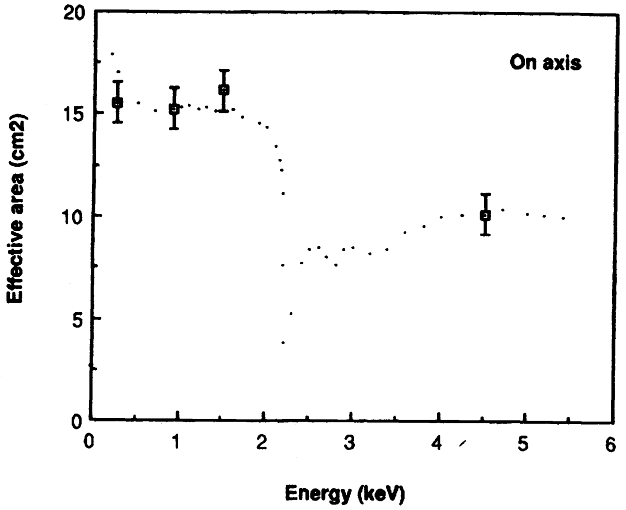

Fig. 9 - D.M. of JET-X. Effective area on axis.

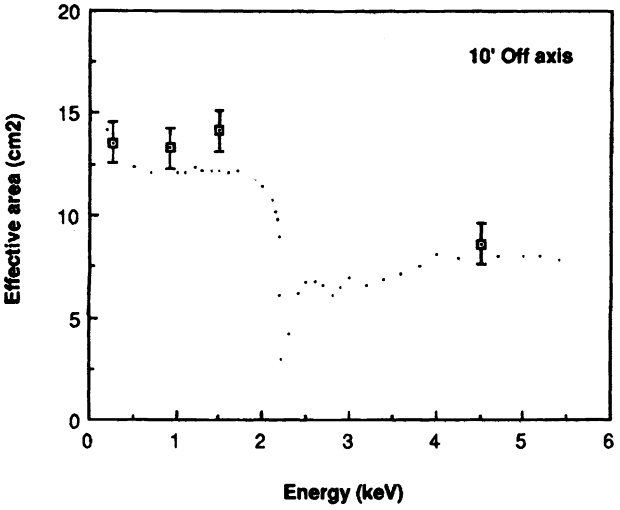

Fig. 10 - D.M. of JET-X. Effective area 10' off axis.

5. CONCLUSIONS

The results and the experience gained in the context of the SAX project[3,4] gave to us the conviction that the replica technique by electroforming the mirrors from mandrels could be efficiently used also for the more stringent requirements of JET-X X-ray optical system, by replacing the double cone approximation used for the SAX optics with a Wolter I configuration and by increasing the thickness of the mirrors in order to achieve better stiffness. The results obtained with the D.M. of the JET-X X-ray optics confirm our assumption.

Assuming that the other 11 mirror shells will have similar characteristics as the one tested on the present D.M. and taking into consideration the tolerances for the integration and on the focal length of the 12 mirrors shells, it is expected to obtain an HPR of 10 arcsec for the whole telescope at 1.5 KeV. This result would be well within the specification of HPR $\leq$ 15 arcsec for the X-ray optical system of JET-X.

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