THE JOINT EUROPEAN TELESCOPE FOR X-RAY ASTRONOMY (JET-X)

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Abstract. JET-X is one of the main payload elements in the Soviet Spectrum-X Gamma mission scheduled for launch in 1993. It consists of two Wolter I X-ray telescopes feeding cooled arrays of CCD's. The combination of good angular resolution and long exposures during the four day orbit of Spectrum-X Gamma, will allow the JET-X telescopes to reach a sensitivity level ten times fainter than that of the Einstein Observatory deep survey. The CCD's will provide good spectral data for many thousands of brighter sources over an energy band ~0.3–10 keV. The JET-X project is an international collaboration involving groups in the United Kingdom, Italy, West Germany and the Soviet Union together with an input from the Space Science Department at ESTEC. A brief description is given of the design and anticipated performance of JET-X together with illustrations of the anticipated scientific results.

1. Introduction

JET-X will be assembled in Western Europe from component parts produced in the UK, Italy and the Soviet Union. Technical and scientific support is also being provided by the MPE group in Germany and by the Space Science Department at ESTEC. Project management and overall systems engineering support are the responsibility of the UK, which will also provide the focal plane assembly and electronics for the two X-ray telescopes and the JET-X attitude monitor. Full funding for the UK role in JET-X was approved by the Science and Engineering Research Council in 1988. Italy is the second major partner, being responsible for provision of the X-ray mirror assembly for each Wolter I telescope and for the co-aligned Optical Monitor. Funding of the Italian involvement in the JET-X programme is being provided by the Agenzia Spaziale Italiana. A key element in the JET-X assembly is the carbon fibre structure which will hold both X-ray telescopes, the Optical Monitor and the star tracker. This structure will act as the optical bench for the system as a whole, providing the stable platform necessary to achieve the target angular resolution. The design of the JET-X X-ray telescopes is based heavily on existing research programmes, a necessary requirement to meet the short timescale set by the proposed 1993 launch of the Spectrum-X-Gamma mission. The X-ray mirrors will be developed by the Osservatorio Astronomica di Brera in Italy, using the replication technique developed for the SAX mission and mandrels manufactured by Zeiss in West Germany (in a programme running alongside the XMM mandrel development). Design and test assistance and the unique Panter X-ray beam facility will all be made available to the JET-X project by the Max Planck Institut fur Extraterrestriche Physik in Garching, bringing to the project a wealth

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of experience gained in the ROSAT programme.

Control and data reception for Spectrum-X-Gamma will be carried out from the Soviet Union, but the complex mission planning, data reduction and scientific analysis will be a broad international effort. It is intended that the JET-X scientific programme (which will be providing observing time on an agreed formula to all participating countries) will be determined on scientific merit, in response to an international A/0, and will be integrated closely with that of SODART the other major instrument on board Spectrum-X-Gamma, (ref. Schnopper, these Proceedings).

2. Instrument Concept

Each X-ray telescope is of Wolter I design, with 12 shells of electro-formed nickel (1mm thick) and 3.5 metre focal length. A fixed array of cooled CCD's is mounted in each focal plane. The baseline optics specification calls for an on-axis resolution of 30 arc sec (HEW), with a design aim of 10 arc sec (HEW), and effective area (2 telescopes) of 360 cm^2 at 1.5 keV and 140 cm^2 at 8 keV. A pair of CCD's will provide efficient coverage of a field of view of 28 $\times$ 21 $arcmin^2$ for each telescope.

The chosen CCD's are derived from a development programme at GEC and Leicester University, also supported by ESA for the XMM project (Wells and Lumb, 1990). Passive cooling to space will maintain the operational temperature of the CCD's on JET-X, (170–180 K), necessary to obtain the required low noise and high energy resolution for X-ray spectroscopy and imaging of faint X-ray sources.

The two X-ray telescopes will be mounted in a common carbon fibre shell, together with the star tracker and Optical Monitor. The star tracker will provide independent attitude for JET-X to an accuracy of $\sim$ 5 arc sec and the Optical Monitor (a Richey-Chretian design of 20 cm aperture, with integrating optical CCD readout) will yield simultaneous optical images to a magnitude limit of $m_v \sim 22$. Further detail of the JET-X Optical Monitor will not be given here, since its design is very similar to that described for XMM (ref. Taylor these Proceedings).

3. Design and Manufacture

The X-ray mirrors will be manufactured by the replication technique developed for the SAX programme. Mandrels, of Wolter I geometry, are being produced by Zeiss, with a super-polished finish of ~5 Å rms. A gold layer is later deposited on the mandrel surface and a nickel layer electroformed on top. On removal of the nickel replica from the mandrel, the gold layer adheres to the nickel, providing the X-ray reflecting surface. Twelve paraboloid – hyperboloid shells form each complete X-ray mirror assembly. The design characteristics of the JET-X nested optics are summarised in Table I and Figure 1 shows the total effective area as a function of energy and off-axis angle.

The CCD's to be used on JET-X are deep depletion devices of type P88930T, derived from an extended research programme at the GEC EEV company at Chelmsford. The use of high resistivity silicon (2000 ohm-cm) ensures good quantum efficiency to $\sim$ 10 keV while thinning of the front electrode structure yields an accept-

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TABLE I
Mirror Characteristics

Field of View	20 arcmin (50% vignetting)
Angular resolution	10–30 arcsec (HEW)
Focal length	3.5 m
Reflecting surface	Gold
Configuration	Wolter-I
Mirror length	2 × 300 mm
Outer mirror diameter	300 mm
Inner mirror diameter	87.5 mm
Shell thickness	2 mm
Number of shells	12
Distance between shells	3–5.8 mm
Surface finish (microroughness)	5 Å rms

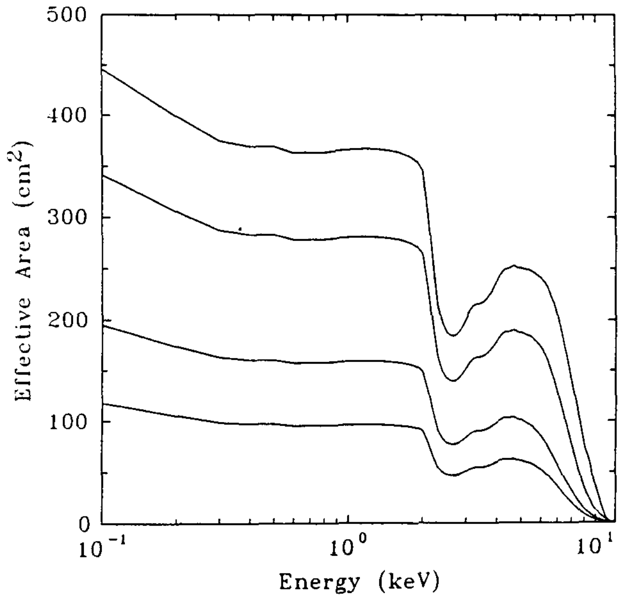

Fig. 1. Total effective area of JET-X (2 modules) as a function of photon energy on-axis, and at off-axis angles of 7.5, 15.0 and 22.0 arcminutes.

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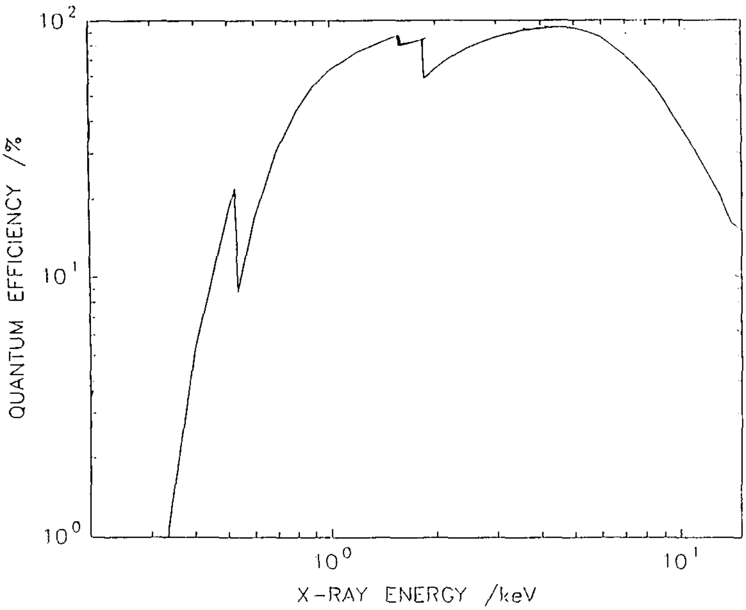

Fig. 2. Quantum efficiency of the P88930T CCD with thinned electrodes and front illumination.

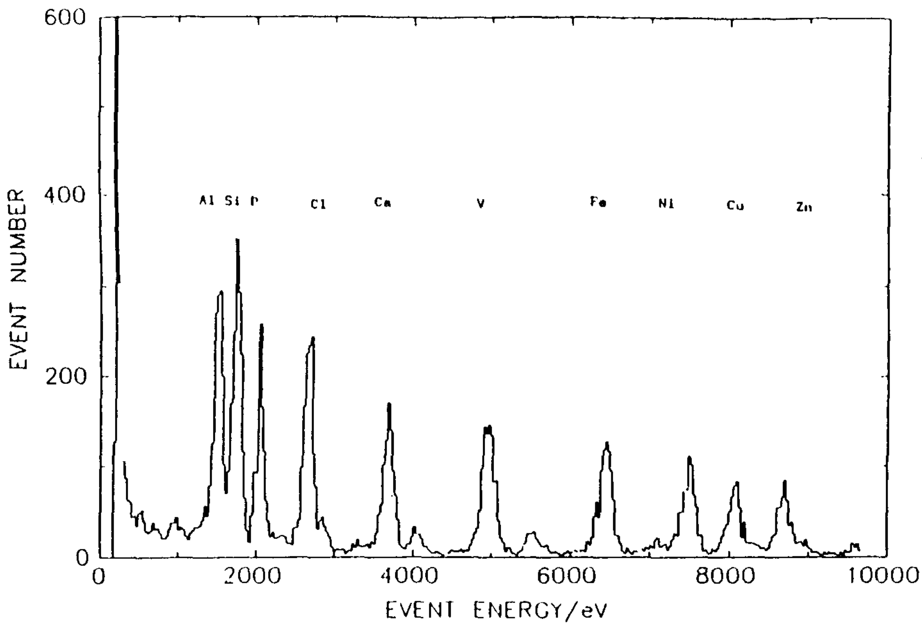

Fig. 3. Measured CCD energy response to a range of characteristic X-ray emission lines in the laboratory.

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TABLE II
Performance Characteristics of type P88930T CCD

Parameter	Predicted Performance
EEV Device type	P8893OT
Pixel format on chip	1024 × 768
Image area per chip	512 × 768
Pixel size	27 μm
Format of chip arrays in focal plane	2 × 1
Dead space between chips	$\lesssim$ 400μm
Depletion depth	40 μm
Dead layer	$\lesssim$ 2000 Å on 50% of pixel
Total detection depth	65 μm
Readout noise	4 electrons
Readout rate (/pixel)	12 μs
Image frame time	3 sec
Operating temperature	180–190 K
Frame store operation	4 amplifiers

able low energy response. Figure 2 shows the Q.E. of this current CCD and Table II lists the basic performance characteristics. Figure 3 shows laboratory data obtained on a number of characteristic X-ray lines to illustrate the energy resolution to be expected in JET-X.

4. Scientific Performance

The scientific potential of JET-X derives from its high angular and good energy resolution, the advantageous orbit of Spectrum-X-Gamma and its timeliness in relation to later, larger X-ray missions, such as AXAF and XMM.

Figure 4 shows the detection sensitivity of JET-X for exposures up to 105 seconds. It can be seen that the low intrinsic noise of the system allows long, photon-limited exposures, yielding:

• a sensitivity limit near 3×10^{-15} erg cm^{-2} s^{-1}, ten times fainter than the Einstein Deep Survey limit, and similar to the ROSAT Deep Survey limit.

• importantly, the higher energy response makes JET-X a valuable extension to ROSAT, for example in determining temperature structures in clusters of galaxies (Sarazin, 1988) and detecting the important Fe K-features in active galaxies (Pounds et al, 1990).

• the limit of $\sim 3 \times 10^{-15}$ erg cm^{-2}/s will remain un-confused (at 40 beams per source) provided the JET-X angular resolution achieves the specified ~30 arc sec. HEW.

Figure 5 shows a second important advantage of the high angular resolution of JET-X, in resolving structure in extended sources.

For example, it can be seen that rich clusters of galaxies will be resolved, at any redshift, while cooling flows should be resolved to a high redshift, depending cru-

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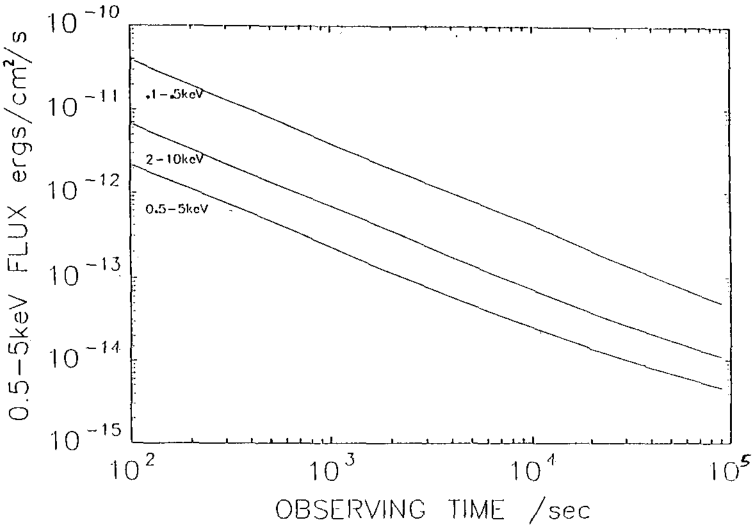

Fig. 4. JET-X point source detection (at 5σ) as a function of exposure time. Input power law of photon index 1.7 and absorbing column 4×10^{20} cm^{-2}.

cially on the resolution actually achieved. The importance of obtaining the highest possible angular resolution in JET-X is emphasised in comparing the linear size of elliptical galaxies, first shown from Einstein Observatory data to contain extended thermal X-ray emission (Fabbiano, 1990).

Figure 6 shows two examples of simulated JET-X spectral data, obtained using the latest performance figures for the optics and flight detectors. Fig. 6(a) illustrates the rich spectral detail expected from the thermal emission of a cluster of galaxies, with $L_{2-10} \sim 10^{45}$ erg/sec, a temperature of kT $\sim$ 4 keV and at a distance of 200 Mpc. The assumed exposure time is 3×10^4 seconds.

Figure 6(b) shows a 3×10^4 simulation for a Seyfert galaxy similar to NGC 4151, but ten times fainter. Here, complex partial covering of the X-ray nucleus and Fe K-fluorescent line and absorption edge features are easily seen.

5. A Five Year Mission Profile

The major scientific goal of JET-X is a study of faint X-ray sources, by spectroscopy, imaging and timing. As noted earlier, the high resolution optics, low noise detectors and 4-day orbit, combine to underpin the value of long exposures for JET-X. With these characteristics in mind a model 5-year mission profile has been constructed (Table III), assuming JET-X will be the prime instrument (i.e. determining the pointing axis) for 180 spacecraft orbits, each with an effective observing time of 2.7×10^5 seconds.

Among the key scientific objectives of each class of observation will be:

deep fields: direct measurement of source counts, to a level corresponding to $\gtrsim 0.5$ of the X-ray background flux, hence identifying the major constituent(s) of the XRB in the 2–10 keV band (and possibly revealing an entirely new class of

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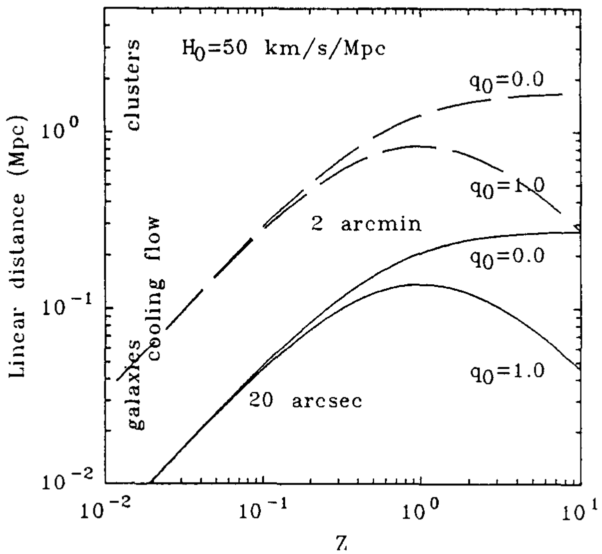

Fig. 5. Linear distance corresponding to a resolution element of 20 arc seconds as a function of redshift. Also indicated are typical sizes for galaxies, clusters of galaxies and cooling flows in clusters.

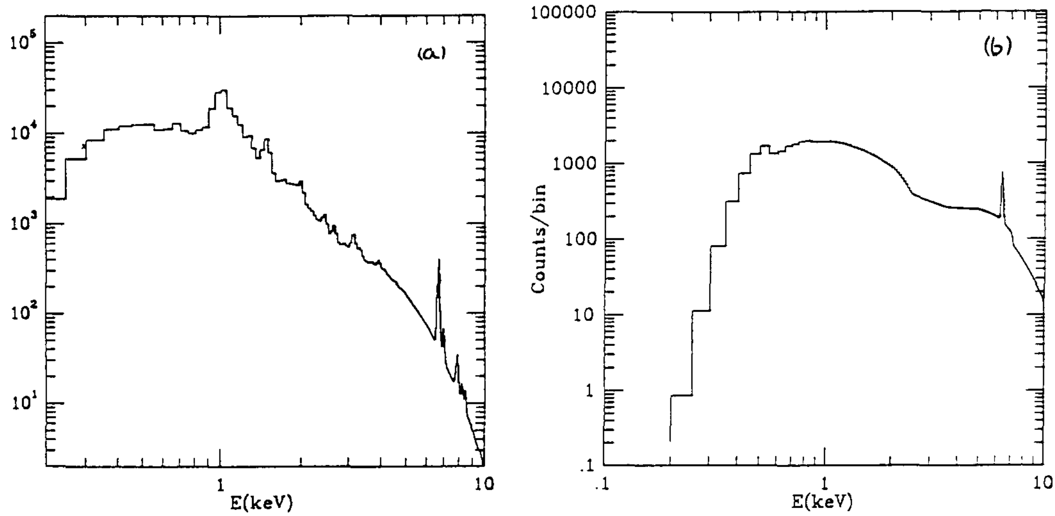

Fig. 6. Simulated JET-X spectra for a 3×10^4 second exposure on (a) a rich cluster of galaxies of $L_x \sim 10^{45}$ erg/sec and kT $\sim$ 4 keV, at 200 Mpc, and (b) a Seyfert galaxy of one tenth the brightness of NGC 4151 with partial covering and reprocessing in cold matter.

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TABLE III
JET-X Prime Mission Profile (5 year mission)

Observation	Cts/source (Percentage)	Flux limit (erg cm^{-2}/s^{-1})	Percentage Exposure	Number	of Time
Deep survey (source counts, XRB)	20	10^{-15}	2.7×10^5	14	8
Medium survey (Spectra of ROSAT Sources)	10^3	10^{-13}	10^5	200	40
Extended source spectra	10^5	$\leq 10^{-11}$	10^5	200	40
Bright sources (in window or timing modes)	$\geq 10^5$	$\geq 10^{-11}$	$\sim 2 \times 10^4$	300	12

faint, strongly evolving sources);

medium survey: broad-band spectroscopy of many X-ray sources detected in the ROSAT survey, yielding information on the possible evolution of the X-ray emission and absorption in AGN, etc.;

extended source spectra: imaging and spectroscopy of rich clusters, elliptical galaxies, SNR, etc. to determine their temperature, density and chemical abundance distributions; hence their mass and evolution;

bright source observations: to study, in particular, the variability in flux and spectrum and hence the geometry of individual emission and absorption features.

Note 1: Total time corresponds to ~ 180 Spectrum X-Gamma orbits

Note 2: 20–100 serendipitous sources are expected in each 105 sec exposure

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