High-Energy Astronomy with the International Space Station

A.N. Parmar
Research and Scientific Support Department, ESA Directorate of Scientific Programmes, ESTEC, Noordwijk, The Netherlands

G. Gianfiglio, J. Schiemann
Microgravity and Space Station Utilisation Department, ESA Directorate of Manned Spaceflight and Microgravity, ESTEC, Noordwijk, The Netherlands

Europe is one of the major partners building the International Space Station (ISS) and European industry, together with ESA, is responsible for many Station components including the Columbus Orbital Facility, the Automated Transport Vehicle, two connecting modules and the European Robotic Arm. Together with this impressive list of contributions, there is a strong desire within the ESA Member States to benefit from this investment by using the unique capabilities of the ISS to perform world-class science. Indeed, ESA has ambitious plans to utilise the ISS for future high-energy astronomy missions.

Introduction

Currently, the ESA Manned Spaceflight and Microgravity and Science Directorates are studying three potential high-energy astronomy missions, in close cooperation: Lobster-ISS, an all-sky imaging X-ray monitor, the Extreme Universe Space Observatory (EUSO), which will study the highest energy cosmic rays using the Earth's atmosphere as a giant detector, and XEUS, the X-ray Evolving Universe Spectroscopy mission. This mission, as the name implies, will do more than use the ISS merely as an observation platform, but rather as a critical element in the construction of a world-class high-energy astrophysics observatory. As such, it will be the potential successor to the present generation of X-ray observatories, such as ESA's XMM-Newton and NASA's Chandra.

A mission is studied to allow its overall design to be elaborated, the scientific and technical feasibilities demonstrated and most importantly the costs evaluated and commitments obtained for all of the necessary elements. These activities are normally part of a so-called 'Phase-A Study', following a successful outcome of which, a project can move forward into the detailed definition and build phases as an approved mission. Each of the three missions described here utilises different aspects of the ISS in order to achieve its scientific goals in a timely and cost-effective manner.

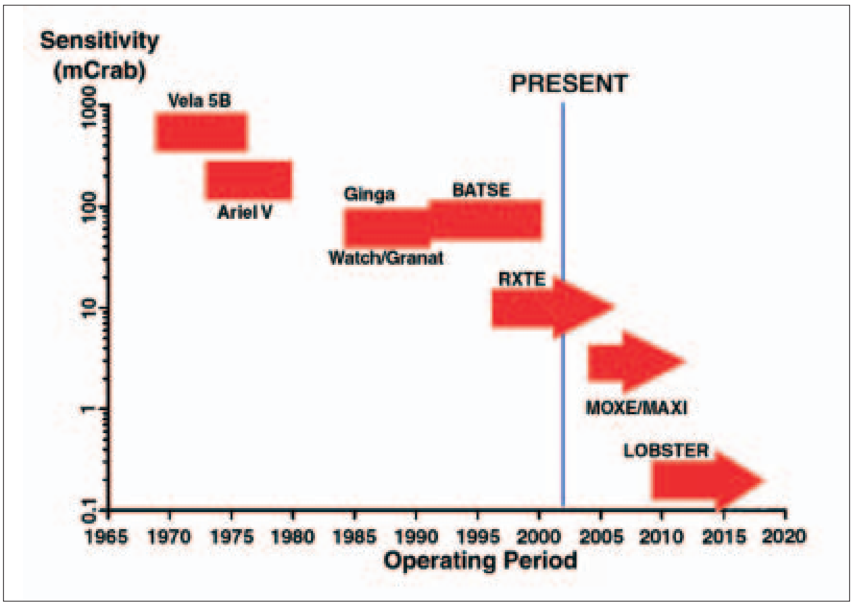


Figure 1. The sensitivity of X-ray all-sky monitors versus operating period. The large increase in sensitivity of Lobster-ISS compared to previous missions is clearly evident.

Surveying the X-ray sky – Lobster-ISS

The X-ray sky is highly variable and unpredictable. A new X-ray source may suddenly appear in the sky, out-shine its contemporaries, and then disappear a few days later. Sometimes an 'old favourite' will surprise everyone by behaving in a totally new and unexpected way. A highly sensitive X-ray mission such as ESA's XMM-Newton observatory only observes a small region of sky at any one time and could easily miss such unpredictable events. This is where an all-sky X-ray monitor, such as Lobster-ISS, can play a vital role. By alerting astronomers to important events occurring anywhere in the sky, powerful observatories can be rapidly re-pointed to take advantage of new opportunities. The importance of this capability was recognised as early as the 1960s and the sensitivity of all-sky monitors has steadily improved (Fig. 1). Currently,

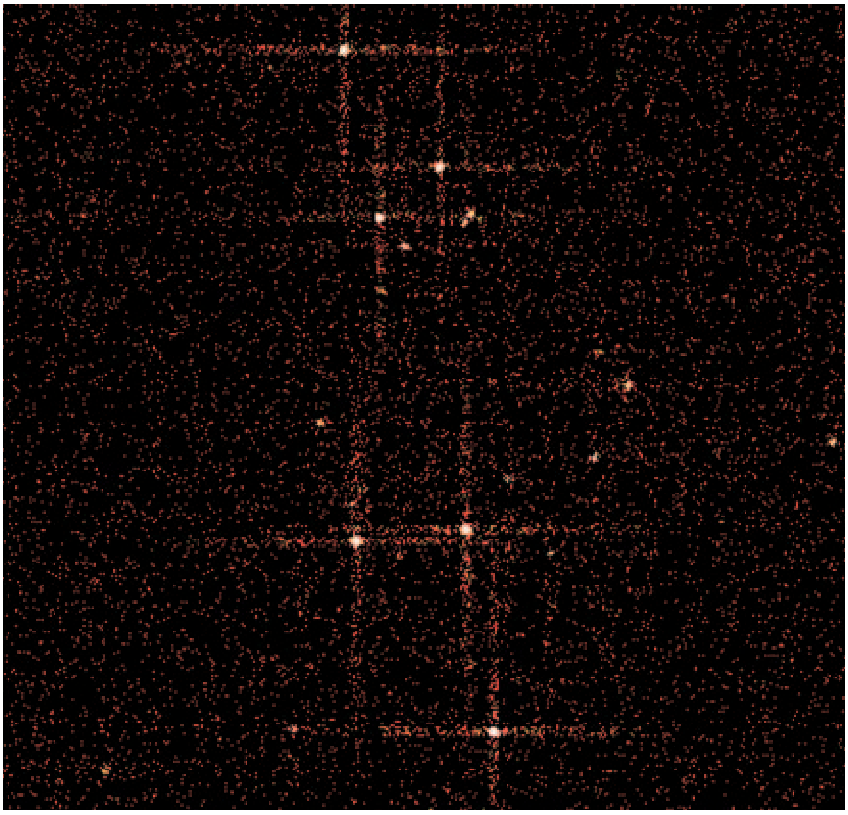
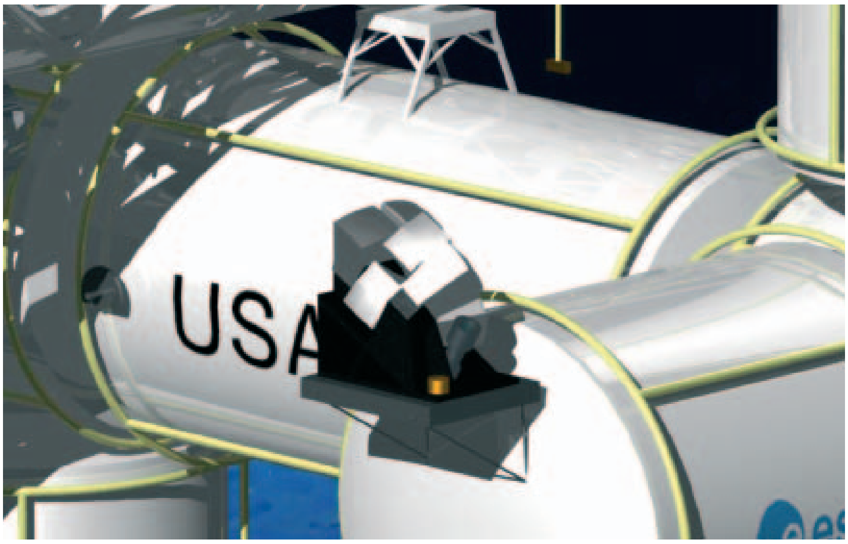


Figure 2. A simulated image of a 10 x 10 deg^2 region of the Large Magellanic Cloud as observed by Lobster-ISS in one day. A total of 22 X-ray sources are clearly detected. The distinctive crosses are a characteristic of the lobster-eye X-ray optics, which focus approximately half the photons into the four arms and the rest into the central point source.

Figure 3. Lobster-ISS mounted on the zenith pointing platform of the Columbus External Payload Facility. The main truss of the ISS runs along the top left of the image, and ESA's Columbus module is visible to the lower right.

astronomers benefit from the all-sky monitor on NASA's RXTE satellite and from the Wide-Field Cameras (WFCs) on the Italian/Dutch BeppoSAX satellite. Even though the WFCs have large, rather than all-sky, fields of view, their ability to provide accurate source positions rapidly played a crucial role in the discovery of X-ray afterglows to gamma-ray bursts. This discovery led to the confirmation that gamma-ray bursts occur in the distant Universe and are one of the most energetic events known. These instruments will be followed in 2004 by the MAXI all-sky X-ray monitor on the Exposed Facility of the Japanese Experiment Module on the ISS. MAXI will offer around a factor 10 improvement in sensitivity, compared to RXTE.



ESA is proposing to fly an even more sensitive (by another factor of 10) all-sky monitor on the ISS in around 2009 called Lobster-ISS. The Lobster-ISS proposal was submitted to ESA's Directorate of Scientific Programmes in response to the Call for Flexi-Mission Proposals (F2 and F3) issued in October 1999. In this Call, proposals based on the utilisation of Columbus and other ISS elements were invited. The Principal Investigator is Prof. G.W. Fraser from the University of Leicester, UK, with co-investigators from the Los Alamos National Laboratory, the NASA Goddard Space Flight Center, the Institute of Astronomy Cambridge, the University of Southampton, the University of Melbourne, and the University of Helsinki.

Lobster-ISS will utilise a novel form of micro-channel plate X-ray optics developed within the ESA Technology Research Programme to provide this unprecedented sensitivity. Lobster-ISS will be the first true imaging X-ray all-sky monitor and it will be able to locate X-ray sources to within 1 arcminute to allow the rapid identification of new transient sources. Lobster-ISS will produce a catalogue of 200 000 X-ray sources every two months, which will be rapidly made available to the astronomical community via the Internet. As well as providing an alert facility, the high sensitivity will allow many topics to be studied using Lobster-ISS data alone. These include the long-term variability of active galactic nuclei and stars, the mysterious and difficult to study X-ray flashes, and the highly topical X-ray afterglows of gamma-ray bursts.

Figure 2 shows a Lobster-ISS image of part of the Large Magellanic Cloud obtained in a 1 day simulated observation. All the bright X-ray binaries, supersoft sources and supernova remnants are visible and their intensities and overall spectra could be monitored on a daily basis. The distinctive 'crosses' visible in Figure 2 are a characteristic of the novel lobster-eye optics. The advantage of this type of optics for an X-ray all-sky monitor is its extraordinarily large field of view. This is achieved by accurately bending the thousands of tiny glass pores that make up each micro-channel plate by exactly the right amount, in order to focus incident X-rays like a telescope. This explains where the name 'Lobster' comes from, since this is similar to how the eye of a crustacean works.

In order to provide the best possible view of the sky, the optimum location for Lobster-ISS is on the zenith pointing of the External Payload Facility (EPF) on ESA's Columbus module (Fig. 3). An initial ESA feasibility study showed that Lobster-ISS could be comfortably accommodated on the standard ISS ExPRESS Palette Adaptor. Unlike a conventional satellite, which orbits the Earth pointing in the same direction, unless commanded otherwise, the ISS orbits rather like an aircraft, keeping its main axis parallel to the local horizon. This is a great advantage for an all-sky monitor since it means that the field of view will automatically scan most of the sky during every 90 minute ISS orbit. A 12-month ESA Phase-A study is expected to start later this year. This will concentrate on the overall instrument design, ISS accommodation, robotic handling, and end-to-end operations.

Probing the highest energy phenomena in the Universe – EUSO

The Earth is being continuously bombarded by high-energy particles known as cosmic rays. While cosmic rays with energies up to 10^{15} eV almost certainly originate from comparatively well-understood objects in our own Galaxy, such as the expanding shocks of exploded stars, understanding the origin of the highest energy cosmic rays with energies above 5×10^{19} eV is one of the great challenges in astrophysics. Although these extreme energy cosmic rays (EECRs), believed to be probably mostly protons, are very rare – only around 1 per square kilometre per century! – they are the most energetic particles known in the Universe, with energies one hundred million times greater than produced by Fermilab's Tevatron, the world's most powerful particle accelerator. Because they are so rare, only about 30 such events have been detected using different ground-based air-shower detectors in the past 30 years. There has been no convincing identification of any of these events with a likely astronomical source.

At such extreme energies, cosmic-ray protons interact with the cosmic microwave background that permeates space, and the distance that an EECR can travel is limited to our galactic neighbourhood. Intriguingly, all the astronomical objects that could conceivably produce EECRs, such as massive black holes, colliding galaxies, or gamma-ray bursts, are all much further away than this. This has led to the idea that the decay of topological defects, or other massive relics of the Big Bang, may instead produce EECRs. If this is indeed the case, then it implies the existence of 'new physics'. These paradoxes are at the heart of the ambitious EUSO mission, to study EECRs from space by using the Earth's atmosphere as a giant cosmic-ray detector. EUSO will observe the flash of fluorescence light and the reflected Cherenkov light produced when an EECR interacts with the Earth's atmosphere (Fig. 4). Direct imaging of the light track and its intensity variations will allow the sky position of the event, as well as the overall energy to be reconstructed. In the same way that Lobster-ISS will benefit from the scanning offered by its proposed zenith location, EUSO will take advantage of the continuous nadir pointing provided by the lowest location of the Columbus EPF. By looking down from here with a 60 deg field of view, EUSO will detect around 1000 events per year, allowing a sensitive search for the objects producing EECR to be made.

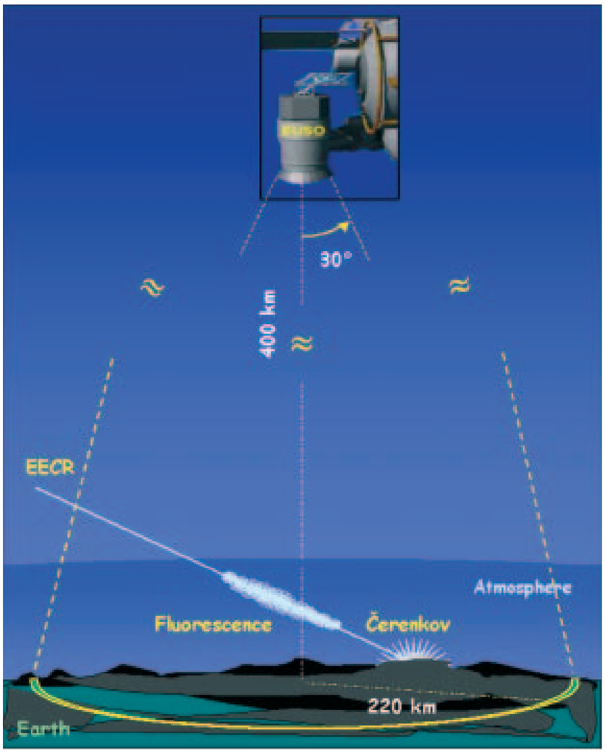


Figure 4. EUSO will observe downwards from the ISS at a height of 400 km with a wide 60 deg field of view and detect the fluorescent and reflected Cherenkov radiation produced when an Extreme Energy Cosmic Ray interacts with the Earth's atmosphere.

Protons are not the only type of extreme-energy particle that will be observed by EUSO. Many models for the production of EECR indicate that large numbers of neutrinos should also be produced. Since neutrinos propagate, on average, much deeper into the atmosphere than protons before interacting, EUSO will be able to distinguish between the two types of particles by selecting on interaction depth and so potentially opening up the new field of high-energy neutrino astronomy (Fig. 5). Since most sources of EECR are expected to be transparent to their own neutrinos, these particles would allow us to observe deep inside a source to view the particle acceleration mechanism directly.

The EUSO proposal was submitted to ESA in response to the same Call for Flexi-Mission Proposals (F2 and F3) as Lobster-ISS. The Principal Investigator is Prof. L. Scarsi from IASF-CNR in Palermo, Italy, who leads a large

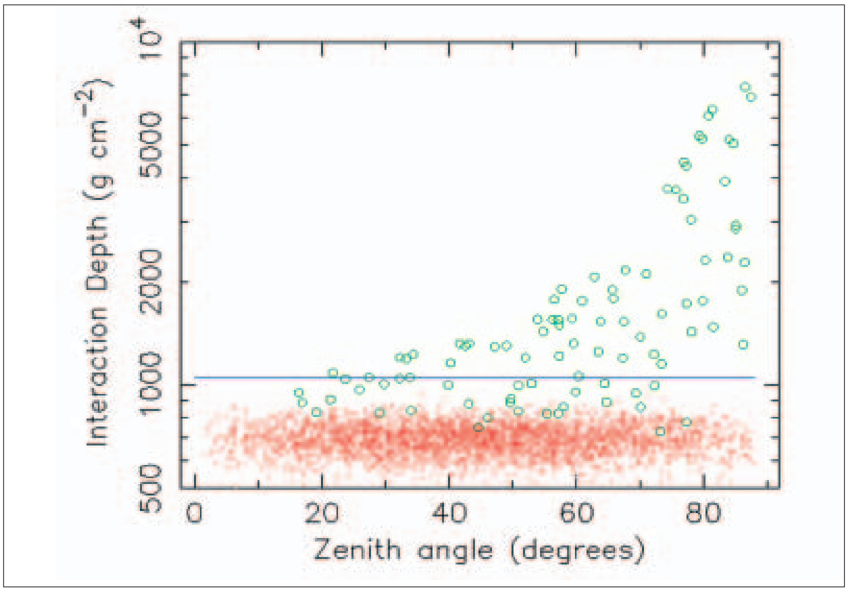


Figure 5. Extreme-energy cosmic-ray interaction depth simulations showing how particle-induced (green circles) and neutrino-induced (red points) events can be distinguished. Any events detected at high interaction depths (corresponding to low altitudes) and high zenith angles will almost certainly be produced by neutrinos.

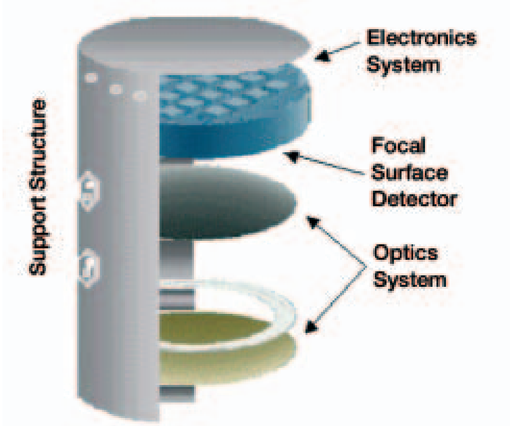


Figure 6. The proposed EUSO layout showing the principal components, including the double Fresnel lens optics and the highly modular focal surface.

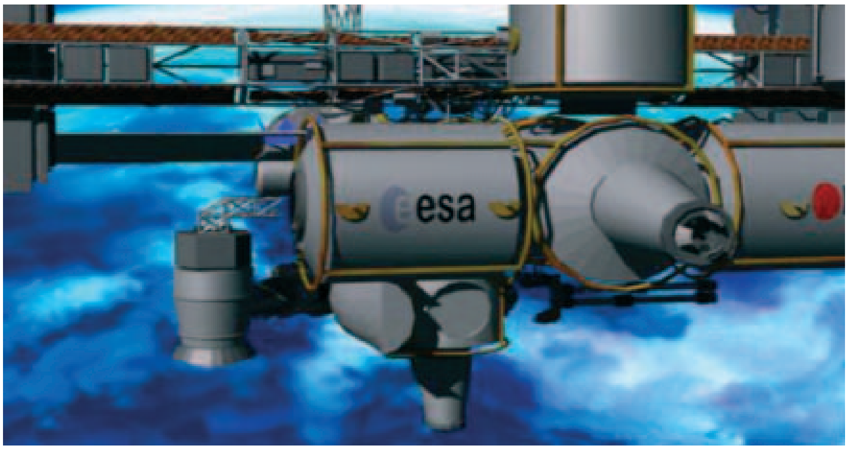


Figure 7. Here EUSO is the cylindrical structure attached to the left side of ESA's Columbus External Payload Facility. From this location it will have an unobstructed view towards the ISS nadir. The docking port for the Space Shuttle and the Japanese module can be seen to the right of the Columbus module.

Table 1. The EUSO consortium – Participating Nations and Institutes

France:	APC, Paris; LAPP, Annecy; ISN, Grenoble; CERS, Toulouse; LPTHE; LAPTH; College de France; Observatoire de Paris
Italy:	CNR-IASF, Palermo; CNR-ISAO, Bologna; University/INFN at Catania, Firenze, Genova, Palermo, Roma, Torino, Trieste; Osservatori Astronomici/INAF at Arcetri and Catania, Istituto Naz. Ottica, Firenze; CARSO
Portugal:	LNP, Lisbon
UK:	University of Leeds
Germany:	MPIfR, Bonn
Japan:	Riken; ICRR/Univ. of Tokyo; KEK; NASDA; Univ. Saitama, Aoyama, Kinki, Seikei and Konan
USA:	NASA/MSFC, Huntsville; Alabama University at Huntsville; UCLA, Los Angeles; Univ. California at Berkeley; Vanderbilt University; University of Tennessee; University of Texas at Austin

consortium of astronomers, cosmic-ray and particle physicists (Table 1). EUSO will consist of a UV telescope with a large collecting area and field of view utilising a lightweight double-Fresnel-lens optics system, a highly segmented focal-surface detector array and sophisticated onboard image processing. The image processing will provide a sensitive discrimination between EECR and other forms of UV radiation such as lightening, meteoroids, aurorae, and man-made illumination. Unlike Lobster-ISS, which fits neatly into the approximately cubic-metre volume provided by the standard ExPRESS Pallet Adaptor, EUSO will need a larger carrier such as the Integrated Cargo Carrier (ICC), due to its 2.5 m diameter and 4 m long cylindrical dimensions (Fig. 6). Following an initial feasibility study, the best way of accommodating such a large and heavy payload on the ISS is one of the key topics of the 12-month ESA Phase-A study started in March 2002 by Alenia Spazio. Figure 7 shows EUSO attached to the Columbus module.

Studying the evolution of the hot Universe – XEUS

The third high-energy mission under study as part of ESA's long-term Horizons 2000 science programme is the X-ray Evolving Universe Spectroscopy mission, or XEUS.

A key goal of this mission is nothing less than the study of the hot matter and unseen dark matter when the Universe was very young by spectroscopic investigations of the first massive black holes. These are believed to have formed when the Universe was only a small fraction of its current age and they may have played a crucial role in the formation of the first galaxies. XEUS will have sufficient sensitivity to derive their masses, spins, and distances by observing X-ray intensity variations and emission lines that have been broadened and distorted by the effects of strong gravity close to the event horizon.

By studying how black-hole masses and spin rates evolve with cosmic time, astronomers will be able to investigate how they grow and the role that they play in the evolution of the galaxies such as our own. One of the most surprising discoveries of the past decade is that the stuff that we are made of, 'normal' matter, makes up only about 5% of the content of the Universe. Most of Universe is made up of mysterious dark matter and dark energy that are not explained by our current understanding of fundamental physics. Most of the normal matter in the Universe is trapped in a dark matter 'cosmic web' as a hot tenuous intergalactic medium (Fig. 8). XEUS will have sufficient sensitivity to characterise the mass, temperature and density of this material using X-ray absorption-line spectroscopy. As well as allowing the nature of the dark matter to be probed, these studies will allow the cosmic history of common elements such as C, O, Ne and Fe to be investigated. Another key science goal for XEUS is to study the formation of the first gravitationally bound, dark-matter-dominated systems (small groups of galaxies) and investigate how these evolved into the massive clusters of galaxies that we see today.

XEUS will be a long-term X-ray observatory consisting of separate detector and mirror spacecraft flying in formation and separated by the 50 m focal length of the optics (Fig. 9). XEUS will be launched by an Ariane-5 sometime after 2012 and will therefore have an initial mirror diameter of 4.5 m, limited by the Ariane shroud's diameter. XEUS requires a revolutionary extension of the technology devised for the X-ray telescopes on XMM-Newton. X-rays are focussed by glancing them off the inside faces of bucket-shaped mirrors through which they pass. To increase the effective area, each of XMM-Newton's three 0.7 m diameter mirror modules consists of 58 individual mirrors. For XEUS, around 500 mirrors will be needed. To achieve the much bigger size and sharper vision required, they will be divided into segments, or 'petals' (Fig. 10). Each petal will be individually calibrated and aligned in orbit to provide a spatial resolution of between 2 and 5 arcsec half-energy width. Narrow- and wide-field imagers will provide fields of view of 1 and 5 arcmin and energy resolutions of 500-1000 and 20 at 1 keV, respectively. It is likely that the narrow-field imager will be a cryogenic detector such as an array of bolometers or super-conducting

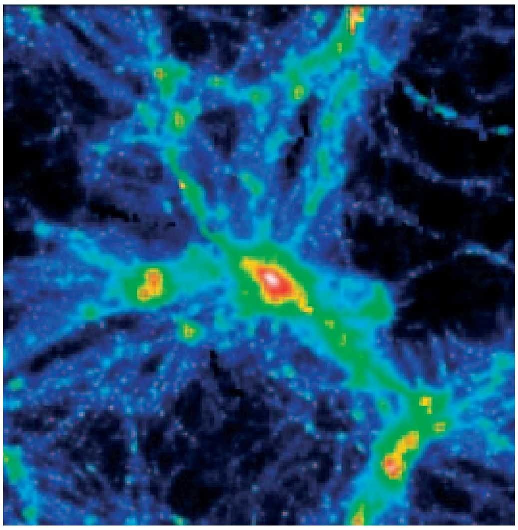


Figure 8. Most of the visible matter in the Universe is trapped in a dark-matter-dominated 'cosmic web' as a hot intergalactic medium. The 'hot spots' visible in this simulation are the building blocks of the Universe, clusters of galaxies.

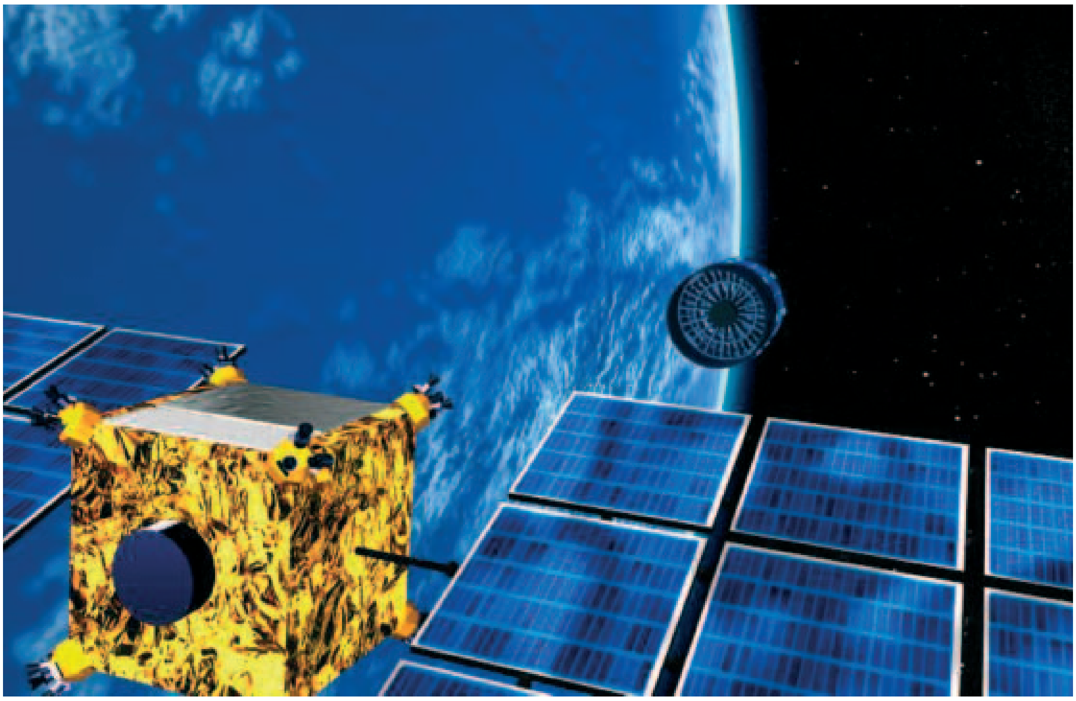


Figure 9. XEUS observing the deep Universe. The detector spacecraft (foreground) maintains its position at the focus of the X-ray mirrors 50 m away to within ±1 mm. The eight sets of thrusters, one at each corner of the rectangular detector spacecraft, are used to maintain alignment and for orbital manoeuvring. The radiator used to cool the cryogenic instruments is located on the upper surface. The cylindrical mirror spacecraft is slowly rotating to minimise the thermal gradients across the highly sensitive mirror surfaces.

tunnelling junctions, and the wide-field device will be based on advanced semiconductor technology. The detector spacecraft will have a sophisticated attitude and orbit control system, manoeuvring itself to remain at the focus of the optics.

After using most of its fuel, the detector spacecraft will dock with the mirror spacecraft and the mated pair will transfer to the same orbit as the ISS. The mirror spacecraft will then dock with the ISS and additional mirror segments that have been previously transported to the ISS will be robotically attached around the outside of the spacecraft (Fig. 11). This will increase the mirror diameter to 10 m and the effective area at 1 keV from 6 to 30 m^2 (Fig. 12). The dramatic increase in sensitivity associated with this expansion means that once the mirror spacecraft has left the ISS to be joined by a new detector spacecraft, complete with the latest generation of detectors, the study of the early X-ray Universe can begin in earnest. The 0.1–2.5 keV limiting sensitivity of XEUS will then be 4 x 10^{-18} erg cm^{-2} s^{-1}, approximately 200 times better than ESA's current X-ray observatory, XMM-Newton, and comparable to those of the next generation of ground- and space-based observatories such as ALMA and NGST (Fig. 13). However, even this figure under-estimates the increase in performance offered by XEUS for high-resolution imaging spectroscopy since it does not take into account the high-spectral-resolution and simultaneous-imaging capabilities of the cryogenic detectors.

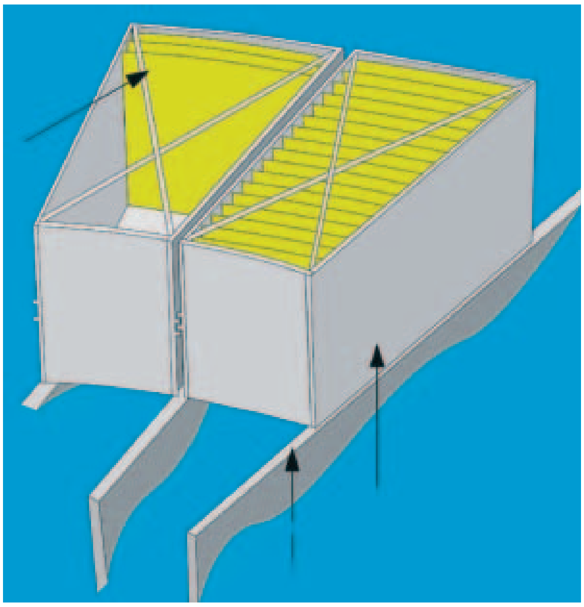


Figure 10. The overall design of the XEUS mirrors showing how the X-ray mirrors will be divided into segments, or 'petals'. The left-hand container is only partially filled with mirror plates.

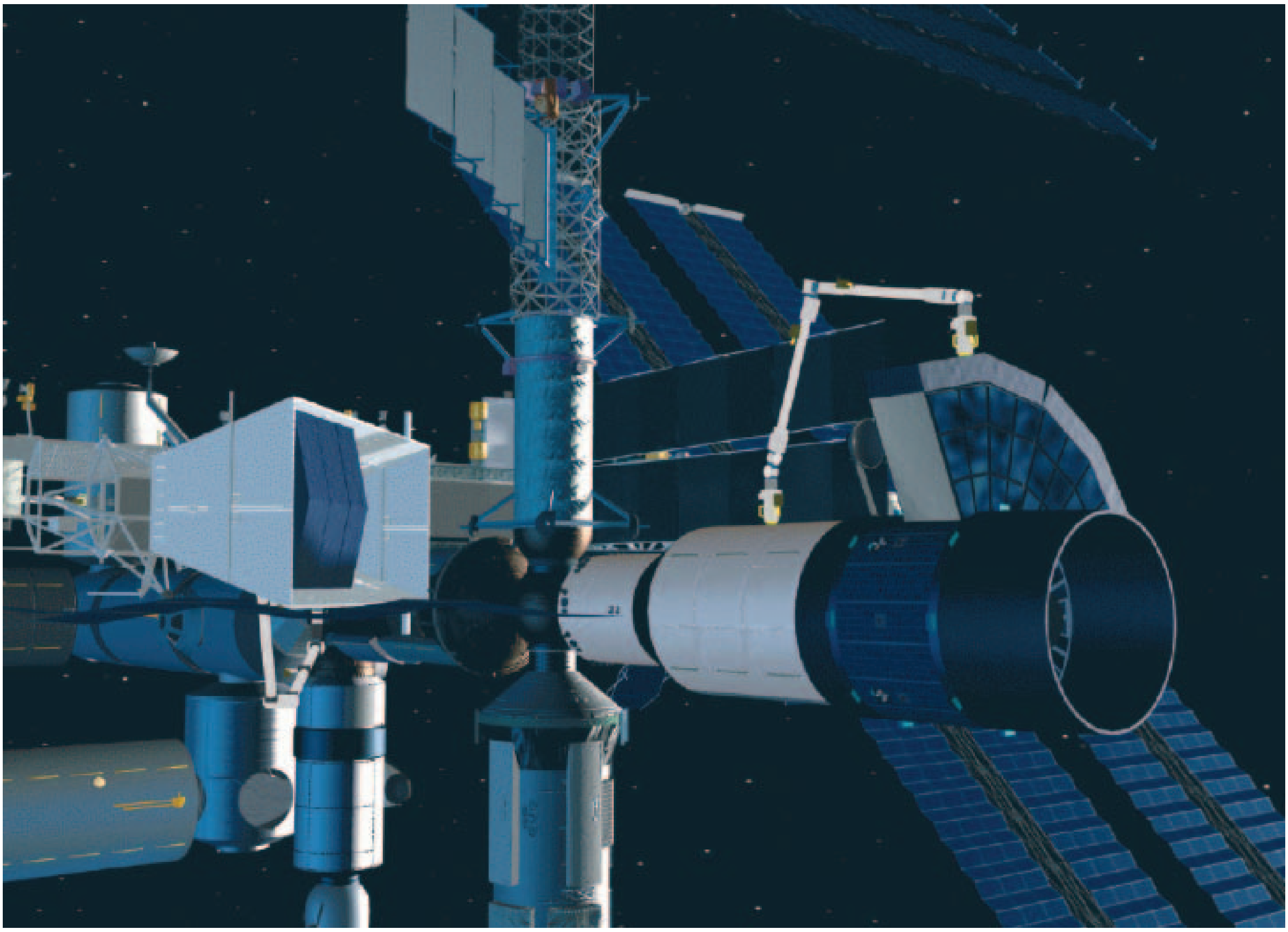


Figure 11. Using the European Robotic Arm (ERA), additional mirror segments are added to the XEUS mirror spacecraft while it is docked at the Russian ISS port. As each segment is added, the mirror spacecraft is rotated to allow easy access by the ERA. The three mirror segments that are waiting to be mounted can be seen in their white transport container on the left.

The scientists and engineers studying XEUS believe that, besides its unprecedented scientific capabilities, one of its strongest selling-points is the imaginative use of the unique capabilities of the ISS to develop a new approach to space astronomy. Following an initial feasibility study, the many new and challenging technologies that are needed for XEUS are being studied in Europe and Japan. It is hoped that in the future Russia and the USA will join this partnership to build the first truly global X-ray observatory. There are many advantages to the phased development afforded by the ISS: detector development can continue even after the launch of XEUS, and the simplicity of the mission design means that the instruments could be repeatedly upgraded during the long lifetime of the telescope. The use of two cooperating spacecraft not only avoids the use of a massive connecting structure, but also means that the detector spacecraft can be upgraded at any time without revisiting the ISS. There is already a great deal of interest from around the World at the prospect of a mission with a sensitivity and spectral capability far exceeding those of XMM-Newton, ESA's current X-ray observatory, which is already producing many exciting new results.

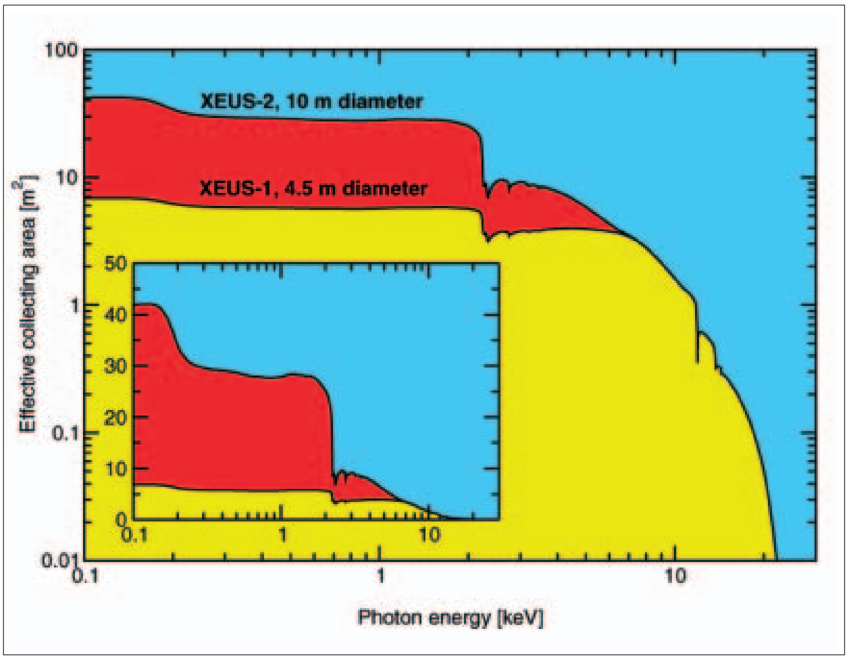


Figure 12. The XEUS mirror effective area at different energies. Directly after launch, XEUS would have a mirror diameter of 4.5 m (XEUS-1). XEUS-2, extended with additional mirror modules by a visit to the ISS, would have a diameter of 10 m and a considerably larger effective area below 5 keV. The inset shows, on a linear scale, the dramatic increase in affective area from XEUS-1 to XEUS-2.

Conclusion

The Lobster-ISS and EUSO studies demonstrate that the ISS is an excellent platform for certain types of astronomical payloads. In the case of XEUS, the ISS provides the only in-orbit infrastructure able to perform the complex operations needed to increase the X-ray mirror diameter from 4.5 m to the 10 m required to meet the science objectives. These capabilities, together with an increasing awareness within the scientific community of the potential of the ISS as a platform for space research, means that many other innovative astronomical applications of the ISS are expected in the next few years.

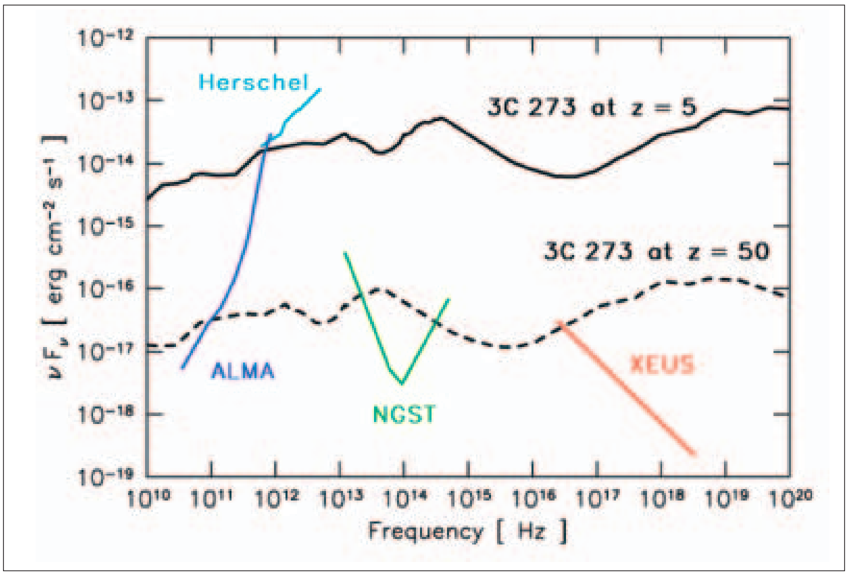


Figure 13. A comparison of the sensitivities of some future missions and facilities. A horizontal line corresponds to equal power output per decade of frequency. For ALMA, an 8 h integration was assumed, for Herschel a 5σ detection in 1 hour, for NGST a 5σ detection in 10 000 s, and for XEUS a 100 000 s exposure following growth at the ISS.

Acknowledgments

The EUSO and Lobster Principal Investigators and the XEUS Steering Committee (M. Turner, University of Leicester; M. Arnaud, CEA Saclay; X. Barcons, CSIC-UC Santander; J. Bleeker, SRON; G. Hasinger, MPE Garching; H. Inoue, ISAS; and G. Palumbo, Bologna Observatory) are thanked for their contributions.

M.C. Maccarone, N. Bannister, A. Reynolds, M. Türler and M. Polletta helped with the production of the illustrations.