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eROSITA – Mapping the X-ray universe

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eROSITA (extended ROentgen Survey with an Imaging Telescope Array) is the core instrument on the Russian/German Spektrum-Roentgen-Gamma (SRG) mission which is currently scheduled for launch late 2015/early 2016. eROSITA will perform a deep survey of the entire X-ray sky. In the soft band (0.5–2 keV), it will be about 30 times more sensitive than ROSAT, while in the hard band (2–8 keV) it will provide the first ever true imaging survey of the sky. The design driving science is the detection of large samples of galaxy clusters to redshifts $z > 1$ in order to study the large scale structure in the universe and test cosmological models including dark energy. In addition, eROSITA is expected to yield a sample of a few million active galactic nuclei, including obscured objects, revolutionizing our view of the evolution of supermassive black holes. The survey will also provide new insights into a wide range of astrophysical phenomena, including X-ray binaries, active stars, and diffuse emission within the Galaxy. eROSITA is currently (Jan 2014) in its flight model and calibration phase. All seven flight mirror modules (plus one spare) have been delivered and measured in X-rays. The first camera including the complete electronics has been extensively tested. So far, all subsystems and components are well within the expected performance.

1 Mission overview

The Spectrum-Roentgen-Gamma (SRG) Mission is a Russian-German astrophysical observatory, comprising two X-ray telescopes (Fig. 1): The Max-Planck-Institut für Extraterrestrische Physik (MPE), Germany, is responsible for the development of the primary payload eROSITA (extended ROentgen Survey with an Imaging Telescope Array). The second instrument is the Astronomical Roentgen Telescope–X-ray Concentrator (ART-XC), an X-ray mirror telescope with a harder response than eROSITA. The ART-XC instrument is being developed by the Russian Space Research Institute (IKI) and the All-Russian Scientific Research Institute for Experimental Physics VNIIEF (Pavlinsky et al. 2013). The X-ray mirrors for the ART-XC instrument are fabricated by VNIIEF and by the Marshall Space Flight Center in Huntsville/Al (Gubarev et al. 2013). The scientific payload is housed on the spacecraft-platform "Navigator", build by Lavochkin Association in Khimki near Moscow. Navigator has been developed as a universal medium-class platform for scientific missions to be launched into different orbits. Navigator platforms are now in service on the Elektro-L mission (since January 2011) and the Spektr-R mission (since July 2011).

Spectrum-RG will be launched in late 2015 / early 2016 from Baikonur in Kazakhstan and delivered to the Lagrangian point L2 using the Zenit-SB rocket and Fregat-SB booster (Fig. 2).

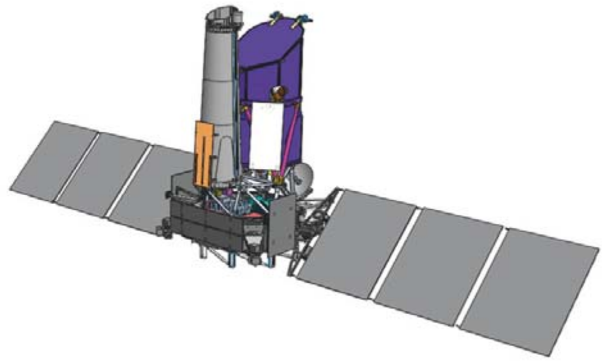

Fig. 1 Navigator platform with the Russian instrument ART-XC in front and eROSITA (courtesy Lavochkin Association).

The SRG observing program is divided into three stages over the 7.5-year mission lifetime: The first $\simeq 100$ days during the cruise to L2 will be devoted to the checkout of spacecraft and instruments, in-flight calibrations, and an early science verification phase. The next four years of operation, SRG will perform a deep survey of the entire X-ray sky. During this survey phase, the spacecraft is permanently rotating around an axis pointing towards the sun, or near the sun in order to avoid an overexposure at the ecliptic poles (where all scan circles overlap). The duration of one revolution will be approximately 4 hours. Since the whole sky is covered every half year, a total of eight scans will be completed after the four years. The all-sky survey program will be followed by 3 years of pointed observations, with open

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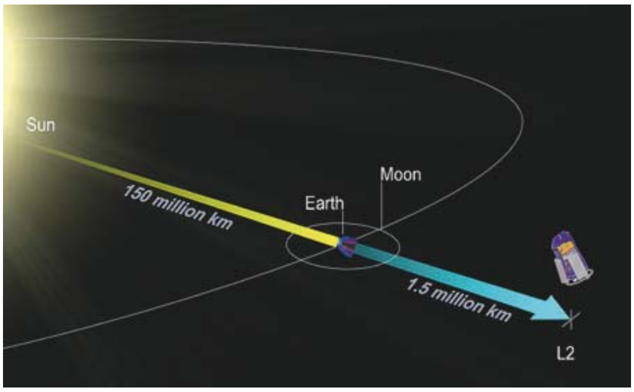

Fig. 2 Schematic view of the location of the L2 orbit of SRG. SRG will become the first telescope to observe the X-ray sky from L2, unaffected by geocoronal X-ray emission (courtesy of K. Dennerl).

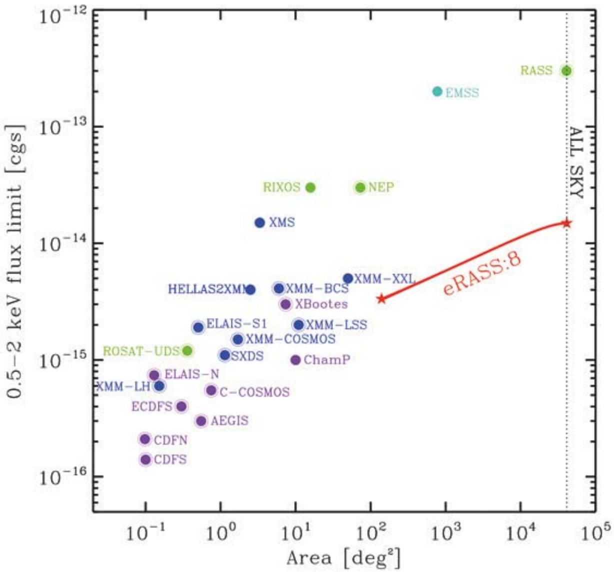

Fig. 3 Sensitivity versus area for eROSITA surveys of point-like (e.g. AGNs and stars) are shown in comparison with existing surveys from Einstein, HEAO-1, ROSAT, XMM-Newton and Chandra. eROSITA outperforms in terms of area covered any existing X-ray survey by more than one order of magnitude at the widest areas.

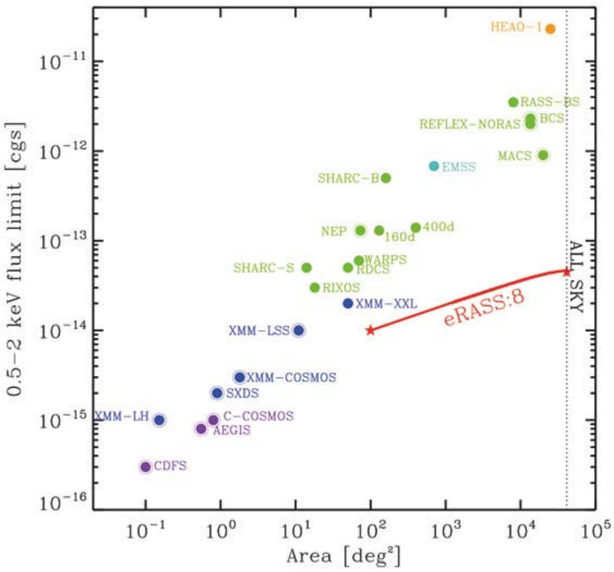

Fig. 4 Same as Fig.+3, but for extended X-ray sources (e.g. clusters).

access through regular announcements of opportunities for the entire astrophysical community. Thereby the accessibility of objects on the sky at any time is restricted by a sun avoidance angle $\pm 20°$ in all directions.

The design-driving science of eROSITA is the detection of very large samples ($\approx 10^5$ objects) of galaxy clusters out to redshifts $z > 1$, in order to study the large scale structure in the universe, test and characterize cosmological models including dark energy (see Merloni et al. 2012 for a detailed description of the eROSITA science goals). eROSITA is also expected to yield a sample of around 3 million active galactic nuclei, including both obscured and unobscured objects, providing a unique view of the evolution of supermassive black holes within the emerging cosmic structure. The survey will also provide new insights into a wide range of astrophysical phenomena, including accreting binaries, active stars and diffuse emission within the Galaxy, as well as studies of solar system bodies that emit X rays via the charge exchange process. Moreover, such a deep imaging survey at high spectral resolution, with its scanning strategy sensitive to a range of variability timescales from tens of seconds to years, will undoubtedly open up a vast discovery space for the study of rare, unpredicted, or unpredictable high energy astrophysical phenomena.

In the soft X-ray band (0.5–2 keV), the eROSITA survey will be about 30 times more sensitive than the ROSAT all sky survey, while in the hard band (2–8 keV) it will provide the first ever true imaging survey of the sky at those energies (Figs. 3 and 4, see also Merloni et al. 2012). With an on axis spatial resolution comparable to XMM-Newton, and a larger effective area at low energies, eROSITA will provide a powerful and highly competitive X-ray observatory for the next decade.

2 The eROSITA_DE consortium

The scientific exploitation of eROSITA data will be shared equally between a German and a Russian consortium. ”Equally” is provided by splitting the sky in two hemispheres. The dividing line intersects the two galactic poles and the Galactic Centre. This simple scheme guarantees a fair share of both galactic and extragalactic areas (see also Fig. 5). A collaboration between the two consortia is encouraged particularly for those kinds of science which requires the full sky for its exploitation.

The German eROSITA consortium comprises seven institutes: five institutes at the universities in Bonn, Erlangen,

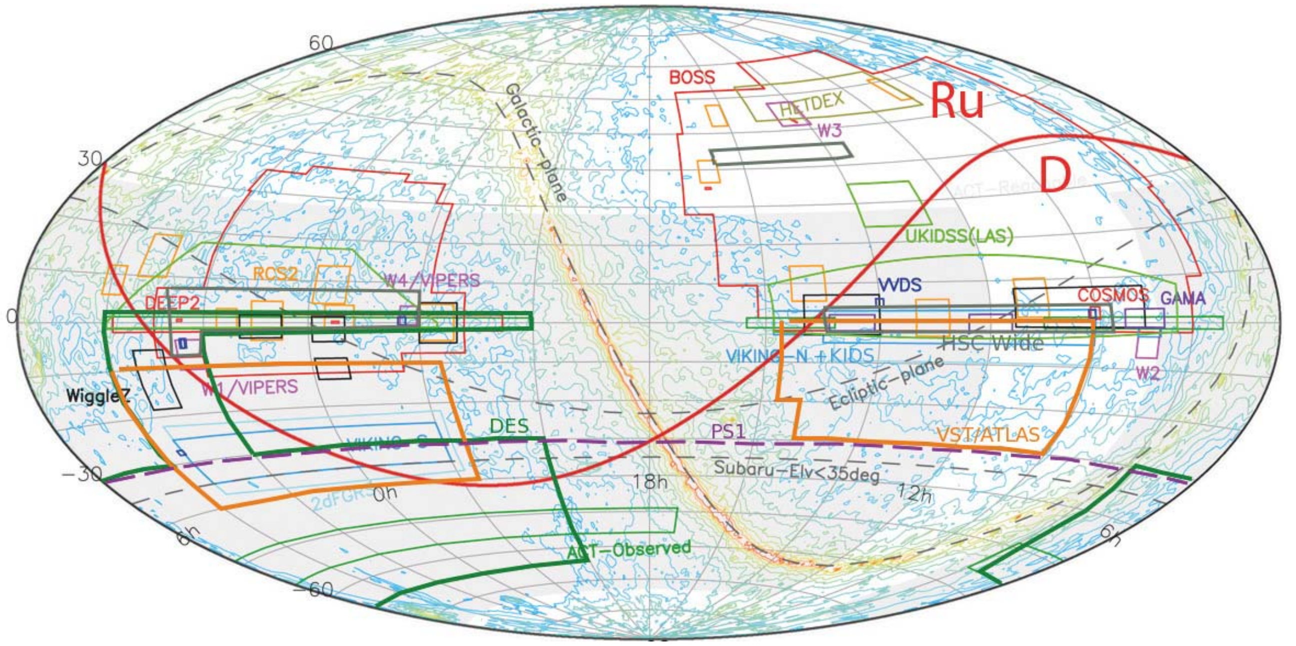

Fig. 5 Multi-band wide area optical imaging surveys (courtesy A. Nishizawa, IPMU) are displayed in equatorial coordinates. The thick red line marks the separation between the German and the Russian eROSITA sky, with the former being the southernmost one. Existing and planned optical/NIR surveys are outlined with colored boxes. PanSTARRS (PS1) survey will cover all area above the dashed magenta line ($\delta > 30^\circ$). Together, DES and PS1 provide the multi-band photometric data needed for cluster and AGN confirmation in the extragalactic German eROSITA sky, as well as the cluster photometric redshift estimation and weak lensing mass constraints.

Hamburg, München, and Tübingen plus the Leibniz Institut für Astrophysik, Potsdam and the Max Planck-Institut für extraterrestrische Physik (MPE), Garching. MPE holds the scientific and project leadership and is responsible for the design, development, integration and test of the eROSITA instrument. Also the development of the pipeline software for processing the eROSITA data is largely based at MPE. The link between the German and the Russian consortia is provided through the Max-Planck-Institut für Astrophysik (MPA) in Garching and the Space Research Institute IKI in Moscow.

German eROSITA survey data will be made public after a two year proprietary period. Periodic data releases are envisaged, e.g. all 6, 24, 48 months. Scientific projects and publications are regulated by ”Working Groups”. There are seven scientific Working Groups (Clusters and Cosmology, AGN, Normal Galaxies, Compact Objects, Diffuse Emission and SNR, Stars, Solar System) and five so-called Infrastructure Groups (Time Domain Astrophysics, Catalogue, Calibration, Background, Follow-up Observations). About 110 scientists have already joined the various working groups. In addition, there are also individual and group external collaborations possible and needed: One example is the need to collaborate with surveys in NIR, optical, and radio (Fig. 5).

A major advantage for eROSITA as the first all sky X-ray survey after ROSAT is that in the intervening 25 years there has been dramatic progress in sky surveys in the optical, NIR, radio, and mm-wave. Moreover, there have been dramatic advances in the use of galaxy clusters for cosmological studies and in the understanding of AGN and the special role that X-ray selected AGN studies can play. These developments should allow a quick progress from the eROSITA X-ray sky toward new discoveries in structure formation and cosmology. As the eROSITA survey will proceed, our goal is to produce catalogues of X-ray selected eROSITA sources that will include state of the art identification of X-ray sources by making use of as much information as possible from the wealth of multi-wavelength data discussed below. The tremendous impact of the ROSAT catalogues (Voges et al. 1999) is a powerful reminder of the importance of such tasks.

3 Instrument description

eROSITA consists of seven identical and coaligned X-ray telescopes housed in a common optical bench. This telescope structure is a system of carbon fibre honeycomb panels connecting the seven Mirror Modules on one side with the associated seven cameras on the other side. A hexapod structure forms the mechanical interface to the S/C bus (Predehl 2012).

Seven single Mirror Modules are arranged in a hexagonal shape. Each of the modules comprises 54 paraboloid/hyperboloid mirror shells (Wolter-I geometry) with an outer diameter of 360 mm and a common focal length of 1600 mm. The on-axis resolution of all mirror modules is around $16''$ HEW at 1,5 keV (see Table 1). The geometry of a Wolter-I mirror system cannot prevent that

Fig. 6 At the end of 2012, the complete eROSITA telescope underwent its qualification program (*left*, during the preparation of the thermal vacuum test). Afterwards, the instrument was disassembled in order to check for damages and failures (*upper right*, removal of the central mirror module). For the qualification, the instrument was equipped with one camera and six mass dummies (*lower right*, showing the seven modules together with the complete thermal system).

photons from X-ray sources outside the field of view reach the camera by single reflection on the hyperboloid. These unwanted photons increase the background but can be suppressed only by an X-ray baffle in front of the Mirror Module. The baffles consist of 54 concentric invar-cylinders mounted on spider wheels, thereby precisely matching the footprint of the parabola entrance of each mirror shell (Friedrich et al. 2012). Magnetic electron deflectors behind the mirrors help in reducing background due to low energy cosmic-ray electrons.

Each mirror system has a CCD camera in its focus. The eROSITA-CCDs have 384$\times$384 pixels on an image area of 28.8 mm$\times$28.8 mm, for a field of view of $1^{\circ}\!.03$ diameter (Meidinger et al. 2013). The 384 channels are read out in parallel using special ASICs ("CAMEX"). The nominal integration time for eROSITA is 50 ms. The CCDs are protected from proton radiation by means of a massive copper shielding. Fluorescence X-ray radiation generated by cosmic particles is minimized by a graded shield consisting of aluminium, beryllium and boron-carbide. For calibration purposes, each camera has its own filterwheel with a radioactive Fe^{55} source and an aluminium/titanium target providing three spectral lines at 5.9 keV (Mn-Kα), 4.5 keV (Ti-Kα) and1.5 keV (Al-Kα). For operation, the CCDs have to be cooled down to –90 °C by means of passive elements (heat pipes and radiators).

The electronics for onboard-processing of the camera data and controlling the entire instrument is housed in 10 individual electronics boxes containing in total 61 large printed circuit boards with approximately 35 000 radhard electronics components.

Two (redundant) startrackers are mounted on eROSITA for accurate boresighting. The dimensions of the telescope structure is approximately 1.9 m diameter times 3.2 m height. The total weight of eROSITA is 810 kg.

Parallel to the instrument hardware also the ground software system for data analysis is being developed, primarily two packages, the Near Real Time Analysis (NRTA) and the Standard Analysis Software System (SASS). The primary use of the NRTA is the health check of the instrument. But the science data can be also analyzed directly after the downlink in order to detect transient events. The SASS is the pipeline machine for the production of calibrated photon event files. It further performs source detections, generates spectra and lightcurves. The end products of the SASS comprise various source catalogues.

Table 1 eROSITA Mirror Modules FM, performance summary from acceptance tests.

	Goal	FM1	FM2	FM3	FM4	FM5	FM6	FM7	FM8
HEW Al-K @ 1.49 keV	15″	16.1	16.8	15.7	16.0	16.2	16.3	15.6	17.1
HEW Cu-K @ 8.04 keV	20″	15.2	15.4	16.7	16.4	16.2	16.2	16.6	18.4
Eff. Area @ Al-K	364 cm^2	391	391	393	369	388	378	392	390
Eff. Area @ Cu-K	21 cm^2	24.8	24.8	25.1	23.8	24.1	25.1	25.0	24.2
Scattering @ Cu-K	15.5 %	10.8	11.2	10.7	12.0	13.3	11.3	11.7	11.4

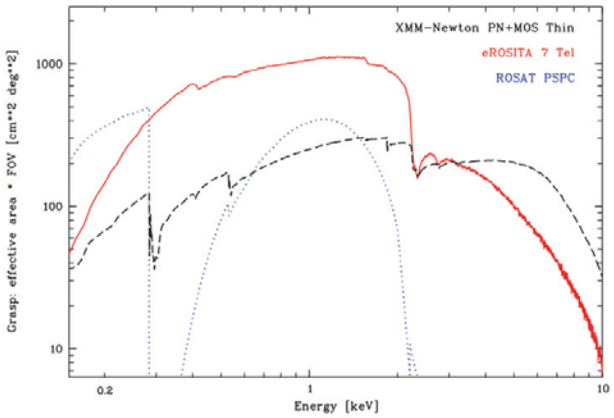

Fig. 7 eROSITA grasp (red curve), defined as the product of field of view times (average) effective area, as a function of energy. For comparison, the grasp of ROSAT PSPC (blue dotted) and XMM-*Newton* PN + MOS thin (back dashed) are shown.

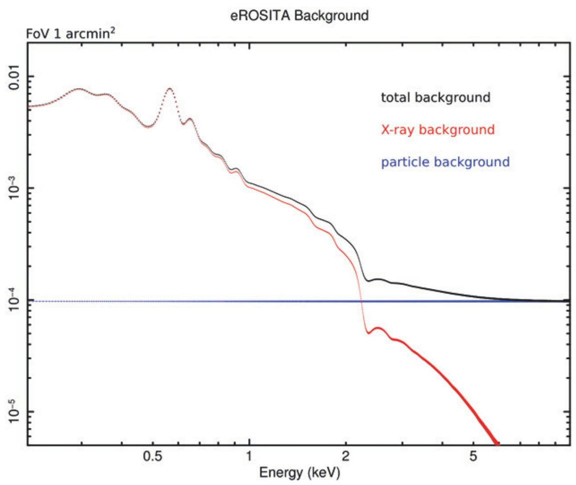

Fig. 8 Simulated (XSPEC) eROSITA background and its spectral components: in red the photon X-ray background (galactic and extragalactic), in blue the particle background and in black the total (courtesy of K. Borm).

4 Performance

The combined effective area (on-axis) of the 7 eROSITA telescopes is about twice XMM-*Newton* EPIC-pn. The "grasp" of eROSITA, defined as the product of field of view times (average) effective area is shown in Fig. 7 in comparison with XMM-*Newton* PN + MOS and ROSAT PSPC (Merloni et al. 2012). This clearly highlights the major breakthrough of eROSITA in the survey speed and capability over a very wide range of energies.

The expected eROSITA background has been simulated based on photon and high-energy particle spectral components. The cosmic diffuse photon X-ray background has been adopted from the measurements with the XMM-*Newton* EPIC cameras, as reported in Lumb et al. (2002). The high-energy particle background has been calculated with Geant4 simulations by Tenzer et al. (2010); see also Perinati et al. (2012). The expected background count rate has been compared with XMM-*Newton* observations, which might provide the best test for the photon background for eROSITA around the Lagrangian point L2 before real photon background data will become available.

5 Status

The complete instrument underwent the qualification program in winter 2012/2013. This program included the standard environmental tests, e.g. vibration, acoustic noise, and thermal vacuum. After these tests, eROSITA was disassembled in order to check for damages and failures. None were found, thus the re-assembling could start again.

eROSITA is currently in its flight model and calibration phase: All eight Mirror Modules are delivered and tested in X-rays (Burwitz et al. 2013). All X-ray baffles, electron deflectors, and filter wheels are manufactured (also eight of each), the thermal system (40 heat pipes, four radiators, etc.) is complete and most of the other mechanical hardware (E-boxes, camera housings, etc.). The development of the complicated electronics but could be successfully finished meanwhile. The test phase of the electronics is almost completed, and the first Camera together with its electronics is being tested was extensively tested in vacuum and with X-rays. It turns out, that everything is within or quite close to the expected performances.

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