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eROSITA's X-ray eyes on the Universe

eROSITA, a new X-ray telescope currently performing an all-sky survey of unprecedented depth, aims to provide insights into dark energy, dark matter, black holes and perhaps new phenomena that have so far been invisible.

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X-ray astronomy is a relatively young field, its date of birth (1962)[1] still alive in the memory of many pioneers of space astronomy. Early experiments used collimators to channel X-rays onto large gas-filled detectors. Focusing X-ray optics later enabled a leap in sensitivity, culminating in the flagship observatories such as NASA's Chandra and ESA's XMM-Newton that dominated the landscape of high-energy astrophysics in the first part of this century.

What kind of sources do these observatories reveal? X-rays trace physics in extreme astronomical sources. Most stars are relatively weak in X-rays, so we see only examples that are particularly active, or those that are being slowly consumed in a binary system by a companion white dwarf, neutron star or black hole. Outside the Milky Way, the most populous sources of X-ray emission are not galaxies, but the supermassive black holes bubbling away at their centres, whose growth may strongly influence their host's formation and subsequent evolution. The majority of the feeble X-ray sky background is produced by the ensemble of these accreting black holes throughout cosmic time.

X-rays also offer the potential to measure the dark components that apparently dominate our cosmos. The primary emission of the hot, tenuous gas that permeates clusters of galaxies is in the X-ray band. In the current cosmological model, clusters signpost the largest concentrations of dark matter in the Universe, forming over time by aggregation from smaller galaxies and groups. Their number density as a function of mass and redshift therefore depends on the competition between the gravitational pull of dark matter and expansionary effects of dark energy. The evolution of the X-ray cluster mass function has been used successfully to measure cosmological parameters, including dark energy[2], in a way that is highly complementary to the measurements based on the Cosmic Microwave Background and other techniques. The possible tensions between orthogonal precision cosmological measurements are perhaps the best way to seed new physical ideas and models.

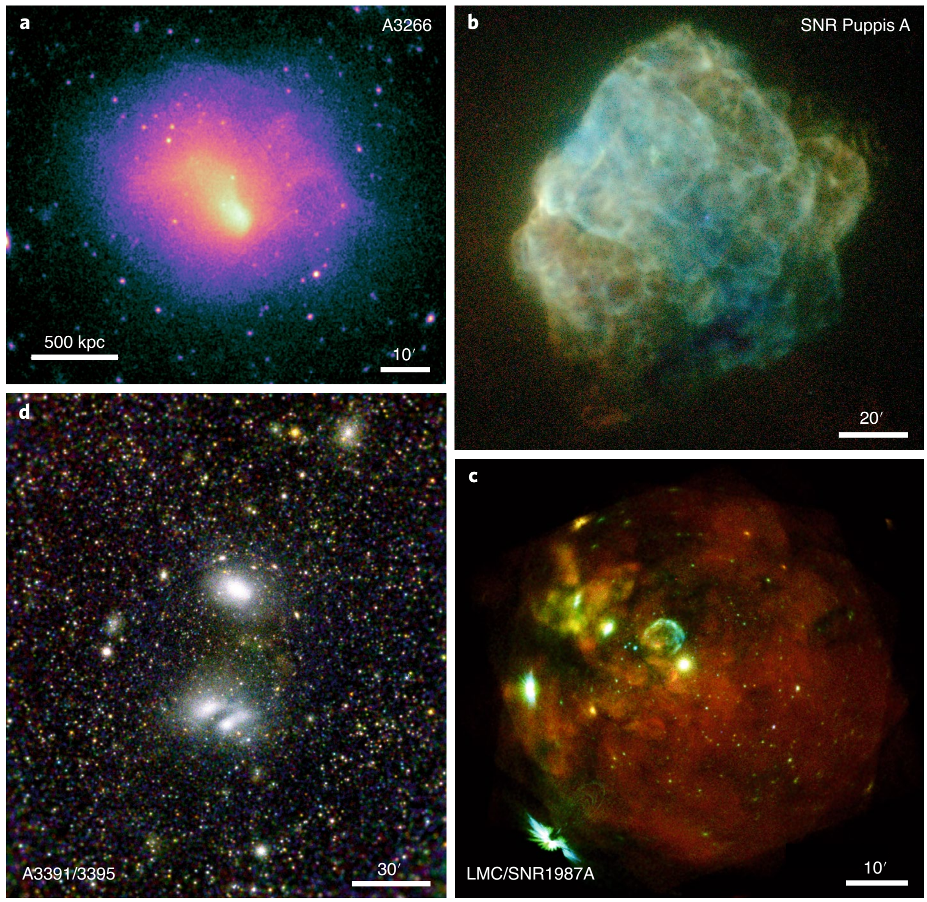

Fig. 1 | Four images taken by SRG/eROSITA during its early operations phases. a, The galaxy cluster Abell 3266 (image taken in the 0.5–2.1 keV energy range, exposure ~74 ks), showing the disturbed and turbulent hot gas. **b**, The supernova remnant (SNR) Puppis A (false colour X-ray image in the energy bands 0.2–0.5 keV, 0.5–1 keV and 1–2 keV, exposure ~60 ks). **c**, Part of the Large Magellanic Cloud, centred on the bright SNR 1987A, showing the hot multi-phase gas permeating the closest neighbour of the Milky Way (false colour X-ray image in the 0.5–1 keV, 1–2 keV and 2–4.5 keV energy bands, exposure ~80 ks). **d**, A wide field centred on the interacting triple cluster system Abell 3391/3395 (false colour X-ray image in the 0.4–0.8 keV, 0.8–1.5 keV and 1.5–3 keV energy bands, average exposure ~20 ks). Courtesy of J. Sanders, P. Predehl, F. Haberl (MPE) and T. Reiprich (AIfA, Bonn). MPE/IKI.

The sample sizes used in X-ray cosmology studies range from a few tens to a few hundreds of objects. The limited field of view of many X-ray telescopes makes it difficult to map large volumes of the Universe in a reasonable amount of time. A notable exception was the ROSAT all-sky survey, performed over six months in 1990, which discovered more than 10% of all X-ray sources known today[3], yielding — among many other riches — large samples of X-ray galaxy clusters that are still used for cosmological studies today. To take the next step in X-ray cosmology, we need a combination of ROSAT's all-sky scanning strategy, with the kind of sensitivity enabled by the technology of more modern X-ray telescopes such as XMM-Newton and Chandra.

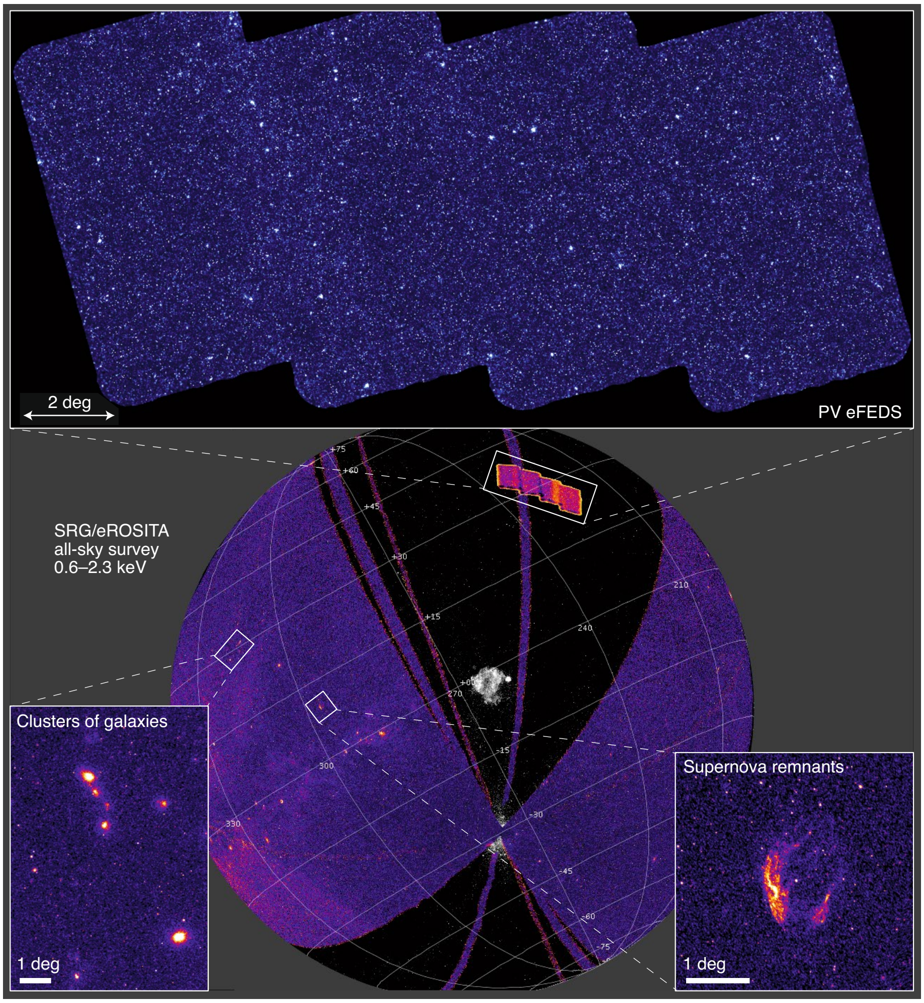

Fig. 2 | The eROSITA all-sky survey. Spherical projection of the eROSITA all-sky survey image in the 0.6–2.3 keV band (purple), taken with an average exposure of ~200 s. In the background, a black and white image of the ROSAT all-sky survey (average exposure ~300 s; http://cade.irap.omp.eu/documents/Ancillary/4Aladin/RASS_IM2). The top panel shows the exposure-corrected X-ray image of the entire SRG/eROSITA performance verification (PV) eFEDS field (~140 deg^2) in the 0.6–2.3 keV band. The average exposure over the field (2.5 ks) is comparable to the final depth that will be achieved over the whole sky at the end of the survey phase of the mission (end of 2023). The two insets at the bottom show details of an extragalactic and a Galactic field, centred on the Shapley supercluster (left) and the supernova remnant PKS 1209-52 (right), respectively. Courtesy of A. Merloni and C. Maitra (MPE) (**a**,**b**); and M. Ramos (MPE) (**c**).

Enter eROSITA

At 14:31 on 13 July 2019, the Russian–German Spektrum Roentgen Gamma (SRG) space mission successfully lifted off from the Baikonur Cosmodrome. SRG has two scientific instruments on board, both operating at X-ray energies: the Extended Roentgen Survey Imaging Telescope Array (eROSITA)[4,5], operating in the 0.2–8 keV band; and the Astronomical Roentgen Telescope X-ray Concentrator (ART-XC)[6], which covers the 4–30 keV energy range.

eROSITA, the primary SRG instrument, was designed specifically to study dark matter and dark energy using galaxy clusters. The design goal was to reach a sensitivity over the whole sky about a factor 30 better than its predecessor ROSAT, sufficient to detect all the most massive clusters (that is, with masses larger than about $2 \times 10^{14}\ M_{\odot}$) lying along our past light-cone. The resulting sample, in excess of 100,000, can provide cosmological constraints comparable with planned Dark Energy Stage IV experiments[7]. Building on current cluster cosmology projects, with sample sizes ranging from a few hundred (with clean X-ray or Sunyaev–Zel'dovich selection[2,8]) to a few thousand (optically selected[9]), the eROSITA sample has the potential to reach sub-percent accuracy for cosmological parameters like σ_8 (the normalization of the power spectrum), Ω_m (the matter density of the Universe) and w_0 (the equation of state parameter), being limited only by systematic, rather than statistical effects.

Designing and building this innovative instrument was a considerable challenge[4]: eROSITA has seven identical X-ray telescopes, each combining a mirror module with 54 nested shells and an X-ray camera placed at its focus. The mirror was constructed using the same replicated Ni technology as XMM-Newton, following the traditional Wolter-I X-ray mirror design also used by Chandra and XMM-Newton. The surface of each mirror shell is extremely smooth, with surface roughness ~0.3 nm, and is coated with gold to increase the reflectivity at grazing incidence of the incoming X-rays. The total throughput of the seven telescopes is comparable to that of XMM-Newton and the overall design optimized for the detection of diffuse X-ray emission from clusters, and to distinguish it from point sources. This sets a minimum requirement on the point spread function of the seven eROSITA telescopes, easily matched by the in-orbit performance, which shows a field-of-view-averaged full width at half maximum of ~10″, about a factor of two better than ROSAT. The X-ray cameras are based on X-ray p–n junction charge-coupled devices (pnCCDs) with 384 × 384 pixels each, delivering a field of view of ~1 deg diameter, with an energy resolution in soft X-rays about twice as good as the pnCCD on XMM-Newton. The cameras are controlled by sophisticated, purpose-built electronics, allowing on-board data compression, and real-time screening of cosmic rays and unwanted background.

Early operations

Ten days after the SRG launch, on 22 July, the protective cover of both telescopes was opened. While ART-XC, with its CdTe detectors operating at −30 °C, could start observations soon after that milestone, eROSITA spent four weeks out-gassing to let any residual dust and dirt molecules evaporate in the interplanetary vacuum. After this the CCD cameras were cooled down to their operating temperature of around −90°C. The commissioning of the seven eROSITA cameras began on 22 August, and lasted eight weeks, about one month longer than expected, mainly due to the discovery of anomalies in the cameras. These are now understood to be due to heavy particles (cosmic rays) causing single-event upsets in parts of the firmware controlling the seven camera electronics. Mitigation strategies and procedures have since been put in place by the operations teams, resulting in a minimal loss of scientific data (<4%), while continuing uninterrupted scientific observations.

A hundred days after launch, on 21 October 2019, SRG completed its 1.5-million-km journey to the second Lagrange point (L2) of the Earth–Sun system, and entered its target L2 'halo' orbit, the first X-ray mission ever to operate at L2. All seven eROSITA X-ray telescope modules had been observing the sky simultaneously since 13 October. Over the following eight weeks, SRG/eROSITA collected its first light images and performed a series of observations designed to calibrate accurately the instruments and verify that the performance of the telescope meets the pre-launch expectations.

Figure 1 shows a small selection of images captured by eROSITA during this calibration and performance verification phase. They highlight the main properties of this unique X-ray telescope — namely its ability to take deep images, which are highly sensitive to both point-like and diffuse emission, over very large areas of the sky. This is realized by virtue of the large field of view, and by the 'raster-scan' observing mode, which delivers uniform exposures over rectangular fields up to ~150 deg^2 at a time.

Fulfilling the promise of the all-sky survey

SRG/eROSITA began surveying the sky on 8 December 2019, and will continue to do so for four years, completing eight independent passes over the whole sky during this period. The combined survey is designed to reach typical point-source sensitivity of about 10^{-14} erg s^{-1} cm^{-2} in the 0.5–2.3 keV band. Figure 2 shows the status of the first survey pass at the time of writing (April 2020): more than two thirds of the celestial sphere are covered, delivering high-quality images of the Galactic and extragalactic sky.

As a preview of eROSITA's capabilities, a mini survey called eROSITA Final Equatorial Depth Survey (eFEDS) was devised as part of the performance verification plan, imaging a >100 deg^2 patch of the sky to a depth comparable to that expected at the end of the all-sky survey (~8 × 10^{-15} erg s^{-1} cm^{-2} in the 0.6–2.3 keV band). These data confirm with high accuracy the sensitivity of the X-ray telescope to its main target classes. Over an area of 1/300 of the full sky, eFEDS revealed more than 20,000 point-like X-ray sources, around 80% of them being distant active galactic nuclei harbouring growing supermassive black holes (including a redshift $z = 5.81$ quasar, the highest redshift object discovered in a 'blind' X-ray survey to date), and most of the remainder X-ray active stars. The mini survey also discovered more than 400 clusters of galaxies, including a few at around $z = 1$, easily recognizable from their extended, diffuse morphology in the sharp X-ray images. It took only four days of observations to generate the eFEDS map, and it will take about 1,500 more to make exquisite X-ray maps of this kind for the whole sky.

The scientific exploitation of the all-sky survey data is organized and directed by two consortia, one in Germany (led by the Max Planck Institute of Extraterrestrial Physics (MPE)) and one in Russia (led by the Space Research Institute of the Russian Academy of Sciences (IKI)). As per agreement between the Russian and German space agencies, the data from the early eROSITA calibration and performance verification observations, including eFEDS, will be released to the public in early 2021. The survey data of the German consortium will be made public in three instalments of increasing depth: in 2022, 2024 and 2026. The data of the Russian consortium will also be made public on a timescale still to be defined. Following the all-sky survey phase, SRG will continue operating in pointed/scanning mode, and the astronomical community will have the opportunity to use eROSITA via open calls for observing proposals.

Considering the landscape of current and future X-ray missions, the eROSITA survey is likely to remain unparalleled for at least the next 15 years. The excellent performance of the hardware, just outlined here, further suggests that the long-term legacy potential of the eROSITA data will be immense, extending well beyond the traditional realms of high-energy astrophysics. ❐

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References

1. Giacconi, R., Gursky, H., Paolini, F. R. & Rossi, B. *Phys. Rev. Lett.* **9**, 439–443 (1962).
2. Vikhlinin, A. et al. *Astrophys. J.* **692**, 1060–1074 (2009).
3. Trümper, J. *Science* **260**, 1769–1771 (1993).
4. Predehl, P. *Astron. Nachr.* **338**, 159–164 (2017).
5. Merloni, A. et al. Preprint at https://arxiv.org/abs/1209.3114 (2012).
6. Pavlinsky, M. et al. *Proc. SPIE* **8147**, 814706 (2011).
7. Pillepich, A., Reiprich, T. H., Porciani, C., Borm, K. & Merloni, A. *Mon. Not. R. Astron. Soc.* **481**, 613–626 (2018).
8. Bocquet, S. et al. *Astrophys. J.* **878**, 55–79 (2019).
9. DES Collaboration Preprint at https://arxiv.org/abs/2002.11124 (2020).

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