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X-Ray Optics: How And What Will We See?

The scope of refractive optics has expanded significantly, significantly covering the area of application of traditional X-ray optics – crystals and mirrors. But for astrophysical problems, X-ray optics of squint gliding remains an indispensable tool. The complexity of the problem lies in the manufacture of multilayer interference mirrors, refractive lenses, and tunable refractive lenses – zoom lenses. To use their potential, X-ray optics of diffraction quality are required. And in the field of X-ray microtomography, the possibilities of increasing sensitivity are hidden in the use of X-ray optical elements: capillary lenses, Fresnel zone plates, asymmetric reflecting crystals (Bragg magnifiers), multilayer X-ray mirrors.

What are the prospects for using X-ray optics? This is covered in the report «Refractive X-ray optics: status, problems and prospects» by A. A. Snigirev (Immanuel Kant Baltic Federal University, Kaliningrad, Russia). Since the first successful experimental demonstration of focusing by refracting lenses of X-rays [1], the field of application of refractive optics has expanded significantly, majorly covering the area of application of traditional X-ray optics – crystals and mirrors. Today, such optics are actively used on all modern high-energy (> 2 GeV) 3rd generation synchrotron radiation sources and free electron lasers (XFEL). Such rapid development is due to successes both in the development of the optical elements themselves and in special tunable devices based on refractive lenses – zoom lenses [2], which allow working in a wide energy range from 2 to 200 keV. In addition to their application in traditional micro-focusing problems, they can also be used as capacitors with an adjustable beam size, collimators providing micro-radial beam divergence, monochromators – low-pass filter [2], devices for suppressing high harmonics [3], Fourier converters [4].

The improved characteristics of beams produced by new 4th generation synchrotron radiation sources with reduced horizontal emittance will open up a unique opportunity for creating efficient beam transport systems based on refractive optics. Due to a significant decrease in the horizontal size of the source and beam divergence, such systems can transmit a photon beam with almost no loss from the source to the sample under study or any intermediate nodes of the optical scheme (mirrors, crystals, lenses, etc.). Apparently, experimental stations will receive significant advantages when using easily tunable systems based on refractive lenses installed immediately after the source. In this regard, the development of radiation- and thermally stable diamond optics is crucial [5–8]. The implementation of a beam transportation system based on refractive lenses will greatly simplify the layout of most new stations [9], which opens up additional possibilities for studying materials under extreme conditions [10, 11]. This will also allow a smooth transition, in the course of modernization, from current beam parameters, at existing stations, to improved characteristics, avoiding major changes in the optical scheme [12].

Applications of refractive optics can be extended to the field of Fourier optics, coherent diffraction, and microscopy [12–16]. To study the 3D structure of photonic crystals and mesoscopic materials [17–19], coherent diffraction microscopy methods and high-resolution diffraction methods using a refractive lens as a Fourier transducer were proposed. The beam formers – axicons [20], which allow creating wavefronts of a given shape, are of a particular interest. In this regard, the use of new additive 3D printing technologies for modeling and creating X-ray micro-optics is difficult to overestimate [21,22].

X-ray interferometry is another promising direction in the development of refractive optics. Recently proposed multi-lens interferometers can generate an interference field with a variable period in the range from tens of nanometers to tens of micrometers [23–25]. This simple way of creating an X-ray standing wave in paraxial geometry opens up the possibility of developing new methods of X-ray interferometry for studying natural and artificial nanomaterials, such as self-organizing biosystems, photonic and colloidal crystals, and nano-electronic objects. Such a device can be used as a classical interferometer for constructing phase-contrast images and radiography, and can also be useful for characterizing the coherent properties of high-energy X-ray sources.

The fact that the progress of recent years in the technology of growth of multilayer interference mirrors (MIS) of normal incidence allows us to begin solving the ambitious task of transferring traditional methods of controlling light beams to extreme ultraviolet (EUV) and soft X-ray (SX) wavelength ranges, the seminar participants learned from a speech by the employees of the Institute of Physics of Microstructures of the Russian Academy of Sciences, Nizhny Novgorod, (N. I. Chkhalo, A. E. Pestov, V. N. Polkovnikov, N. N. Salashchenko, M. N. Toropov) «Diffraction Quality X-ray Optics: Technology, Metrology, Applications».

Due to the short wavelength, low scattering and resonant nature of the interaction with matter, radiation of this range provides unique opportunities for nanophysics, nanotechnology and nano-diagnostics of substances. The largest amount of information about the physical processes occurring on the Sun is obtained from studies of the corona of the Sun in the EUV and SX ranges. Broadband MIS allows you to transport, focus, conduct spectral analysis of atto- and sub-atto-second pulses of electromagnetic radiation without «blurring» the wave packet, or even shorten it in time.

To use the potential of MIS for the image and transport of beams without distortion of the wave fronts, diffraction-quality optics for the X-ray range are required. Compared to traditional optics, its accuracy should be at least two orders of magnitude higher. Traditional methods of manufacturing and studying mirrors do not provide these requirements. The report reported on new methods of fabrication and characterization of diffraction-quality optics developed at the IMP of RAS for the EUV and SX ranges. Examples of the use of the discussed X-ray optical elements of optics for extraterrestrial astronomy, X-ray microscopy, and lithography were presented.

The report «Multilayer Beryllium-Based X-ray Optics» (V. N. Polkovnikov, N. N. Salashchenko, N. I. Chkhalo, Institute of Microstructure Physics of RAS, Nizhny Novgorod) was devoted to the study of beryllium-containing multilayer mirrors (MM). Back in the 1990s, beryllium was used in the soft X-ray (SX) and extreme ultraviolet (EUV) ranges as a weakly absorbing material (spacer). However, the Be-based spacer MMs provided high reflection coefficients only in a very narrow wavelength range of 11.2–12.4 nm. At other wavelengths, beryllium-containing MMs were inferior to traditional MMs based on Si, Al, and Mg spacers. In the course of our work, it was shown that in the wavelength range $\lambda>17.1$ nm, beryllium has a unique combination of the imaginary and real parts of the refractive index. This makes it possible to use Be as a scattering material and, as such, simultaneously obtain record high reflection coefficients and spectral selectivity. The smoothness of the dispersion dependence of the refractive index Be allows it to be used in the short-wavelength part of the SX spectrum as the basis of the MM intended for use in a wide range of wavelengths. In addition, the application of the barrier layer technique allowed us to achieve record reflection values of beryllium-containing MM in the range of 11.2–14 nm.

Methods for increasing resolution and sensitivity in microtomography using X-ray optical elements were considered in a report by V. E. Asadchikova, A. V. Shubnikov Institute of Crystallography of the Federal Research Center «Crystallography and Photonics» of RAS. Currently, X-ray tomography is a widespread method for studying the spatial structure of objects in various fields of science and technology. Computed (X-ray) tomography has become one of the main diagnostic methods in modern medicine. However, the spatial resolution and sensitivity achieved in these devices are insufficient for using the devices in many other applications. A significant drawback of serial X-ray tomographs is the fact that the instruments provide the ability to determine the absorption only in the relative Hounsfield scale.

An increase in resolution and sensitivity at present (due to a number of limitations) can be achieved only with a decrease in the field of view. For this reason, research is actively ongoing in the field of X-ray microtomography. The main possibilities for increasing resolution are projection magnification using microfocus sources and / or the use of X-ray optical elements. These include capillary lenses, Fresnel zone plates, asymmetric reflective crystals (Bragg magnifiers), and multilayer X-ray mirrors, which, however, can only be effectively applied to soft X-rays. Note that the use of monochromatic radiation allows us to determine the values of linear absorption coefficients, which significantly improves the quality of the information received.

The report showed the possibilities of using these elements in X-ray microtomography both in our country and abroad. The speaker paid special attention to the issue of increasing the sensitivity of X-ray tomographs by applying phase-sensitive effective methods. This is also achieved using various X-ray optical elements. In addition to the above, the latter also include diffraction gratings (Talbot interferometry). Examples were given of studying the three-dimensional structure of samples of different nature with varying spatial resolution.

X-ray optics of oblique incidence and its application in the Spectrum-RG orbital astrophysical observatory project were considered in a report of the same name by a group of authors from Space Research Institute of RAS and Russian Federal Nuclear Center – All-Russian Research Institute of Experimental Physics, Sarov (M. N. Pavlinsky, A. A. Lutovinov, A. Yu. Tkachenko (Space Research Institute of RAS, Moscow); S. V. Grigorovich (Russian Federal Nuclear Center – All-Russian Research Institute of Experimental Physics, Sarov). From 2007 to 2016, the work was carried out at the Space Research Institute of RAS and Russian Federal Nuclear Center – All-Russian Research Institute of Experimental Physic to develop the ART-XC squint incidence X-ray mirror telescope for Spectrum-RG orbital astrophysical observatory (the launch of the observatory is scheduled for June 21, 2019.) Within the framework of these works, the development of technologies for the manufacture of X-ray mirrors by the method of electroforming based on nickel and nickel-cobalt with iridium coating was carried out. The task was complicated in the manufacture of mirrors allowing operation up to energies of ~30 keV with an angular resolution of ≤1“ in the field view more than ≥30“. The participants of the discussion were presented with technological developments, the solution of the problem of metrological support and the results of ground tests at a specialized calibration stand of oblique X-ray optics drops coupled with the developed position-sensitive and CdTe-based spectrometric semiconductor detector. Together, the seven mirror systems of the ART-XC telescope provide an effective area of ~460 cm^2 along the axis of view at an energy of 8 keV.

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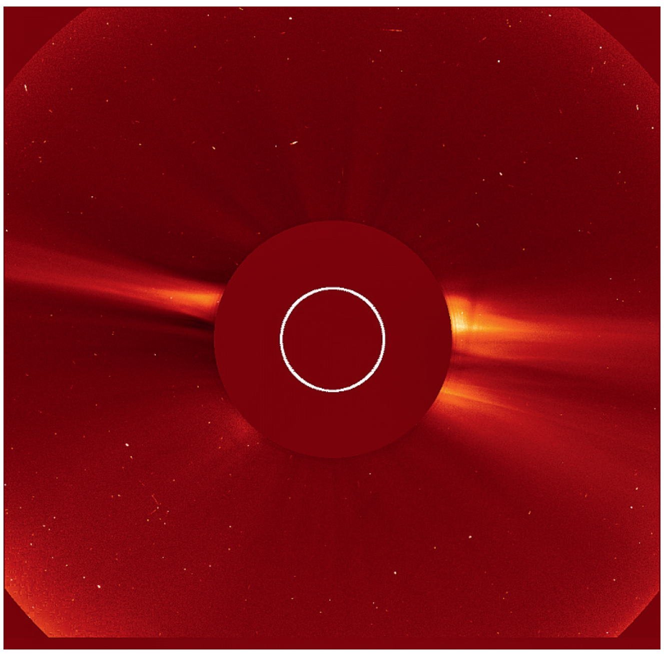
Earth in the Arms of the Sun: Heliophysics and Space Weather

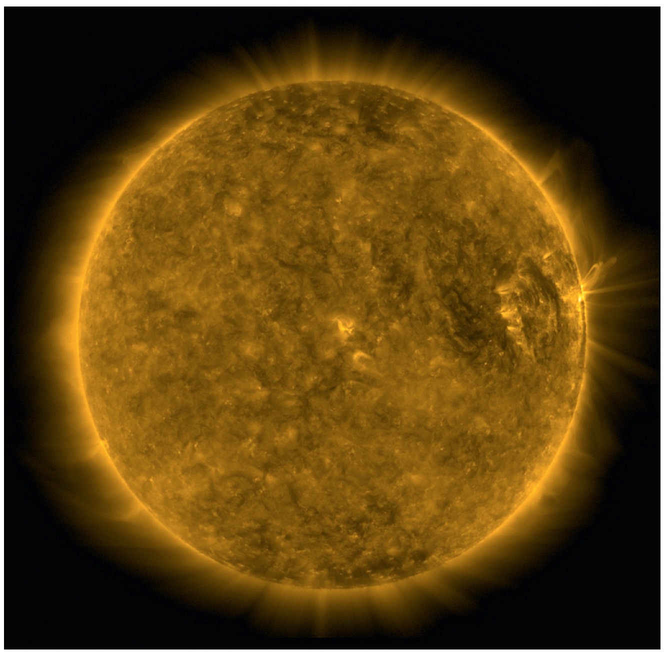
The regular meeting of the Scientific session of the Department of Physical Sciences (supervised by R. A. Suris, academician of the RAS) was held on June 5, 2019. The topic has combined the reports on the latest results in research on the Sun and its effect on space weather.

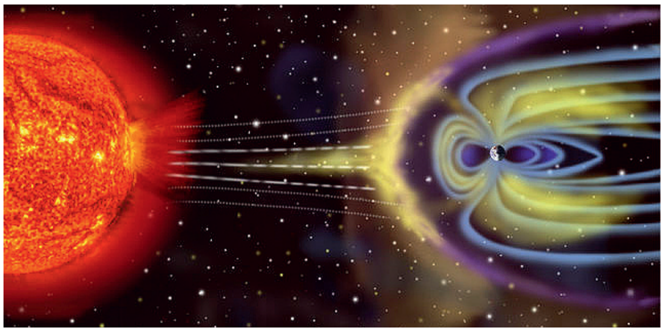
S. A. Bogachev, Doctor of Technical Sciences (Lebedev Physical Institute, Moscow), spoke about the new results of observing the Sun with ultra-high spatial resolution. Long studies of the Sun have led to the generally accepted conclusion that the energy of the observed solar activity is insufficient to explain the fundamental properties of the solar corona – above all, its high temperature. In 1988, the American astronomer Eugene Parker suggested the existence of so-called nano-flares on the Sun – events whose power is 6–9 orders of magnitude lower than the power of a large flare, but whose integrated energy release can be orders of magnitude higher than the large-scale activity component. Over the past 10–15 years, solar nano-flares, as well as an intermediate class – microflares – have become an observable phenomenon.

At the same time, evidence appeared of the existence of a much wider set of small-scale phenomena on the Sun – bright X-ray points, spicules of various types, Ellerman bombs. The report presents the results of domestic space experiments conducted by the Russian Academy of Sciences and the Russian Space Agency, as well as the latest data from foreign space observatories. Within the framework of the Federal Space Program of the Russian Federation for 2016–2025, it is planned to create a specialized solar observatory «ARKA», which is to provide images of the corona of the Sun with an angular resolution of 0.1 arc seconds (less than 100 km) for the first time. It is hoped that the information obtained will make it possible to make decisive progress in understanding the balance between large-scale and small-scale energy in the Sun, and maybe finally answer the fundamental question – what warms the corona of the Sun.

The report «Modern Look at the Solar Wind, from Micro to Macro Scales» (A. A. Petrukovich, M. O. Ryazantseva, H. V. Malova, Space Research Institute of RAS, Moscow) was devoted to one





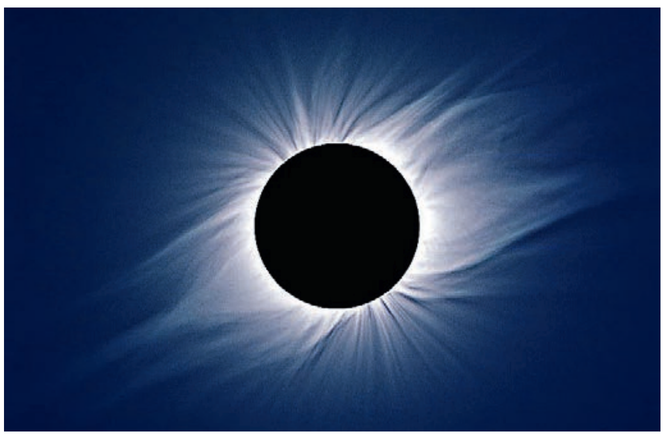


of the most important elements of the solar system – the solar wind. Solar wind plasma is a unique laboratory of a specific astrophysical medium with the dominance of flowing energy. A review of current results on the study of the origin and dynamics of the solar wind covered the structure of several scientific fields at once, emphasizing the logic of research. At the microscale, the spectral structure of flow turbulence was determined, new types of isolated nonlinear structures with characteristic sizes of the order of the ionic kinetic scale were revealed. Collisions of solar wind flows between themselves and with planets form shock waves. Multipoint satellite observations make it possible to determine the mode of plasma oscillations responsible for creating a collisionless wavefront. At medium scales (up to a million kilometers), structures that originate on the Sun and are modified during propagation dominate. These structures play an important role in the generation of magnetic activity on Earth. An analysis of the dynamics of such structures shows an interesting possibility of improving the forecast of their development with an increase in their size, which is of practical importance for forecasting magnetic storms for monitoring solar wind. At macroscales of the order of the heliosphere, the structure of the solar wind is determined by the configuration of the main magnetic field of the Sun and can be traced on interplanetary spacecraft.

V. D. Kuznetsov (Institute of terrestrial magnetism, ionosphere and radio wave propagation (IZMIRAN), Troitsk) made a review «Heliophysics: From Observations to Models and Applications». Based on observations and building physical models, he considered the problematic issues of solar physics – global fluctuations in the interior of the sun, trigger mechanisms of the most powerful manifestations of solar activity – flares and mass ejections, heating of the solar corona, shock waves in a collisionless solar wind plasma. The studied phenomena of solar activity are considered as sources of space weather in near-Earth outer space were considered in the appendix to the practical issues of the impact of its factors on the spheres of human activity on Earth and in space. The report examined the structure of scientific problems aimed at solving such urgent problems of solar physics as the variability of the duration and height of solar cycles, the trigger mechanisms of solar flares and mass ejections, the mechanisms of particle acceleration in the solar atmosphere and heliosphere, the heating of the solar corona and the acceleration of the solar wind, and some others. These tasks are being addressed within the framework of the Intergeliozond space project of the Federal Space Program of the Russian Federation.

M. I. Panasyuk (SINP MSU, Moscow) spoke about the existing radiation fields in space and the need in connection with their magnitudes of planning space missions. For on-board electronics and long-term manned flights, the problems associated with the presence of the heavy component of charged particles and secondary neutron fields in cosmic radiation are becoming increasingly relevant. The presence of radiation in outer space is due to the existence of radiation fields. These include: the Earth"s radiation belts (ERB) and some other planets of the solar system, galactic cosmic rays (GCR) and solar cosmic rays (SCR). These radiation components are composed of various particles, including protons, electrons and heavy nuclei (ions) of chemical elements:

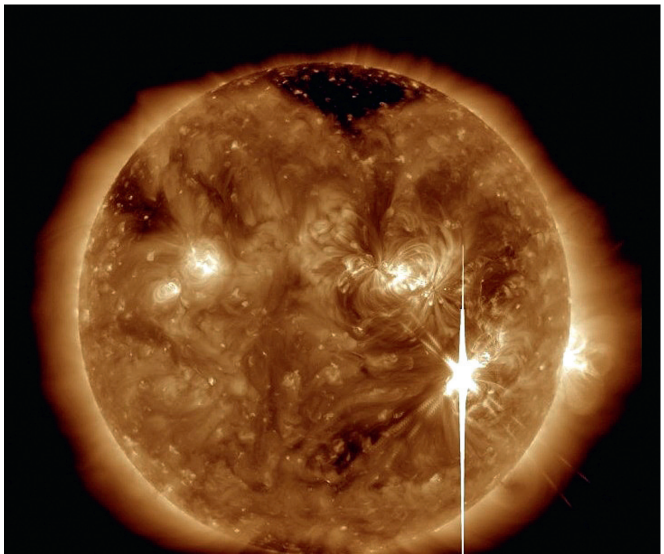
- GCR, the flows of which penetrate into the solar system from our and other galaxies;



- SCR, which occasionally appear in the solar system as a result of the generation of chromospheric flares and coronal mass injections on the sun;
- ERBs trapped in the magnetic trap of the Earth"s magnetosphere, which holds particles of solar and atmospheric (ionospheric) origin, as well as nuclear reaction products resulting from the interaction of cosmic rays with the Earth"s atmosphere.

It has been established that the energy range and level of particle fluxes in radiation fields, and, consequently, the level of radiation hazard vary significantly, due to both the spatially inhomogeneous distribution of these fluxes in interplanetary and near-Earth space, and the changes in these fluxes in time due to the temporal variability of physical processes in the galaxy and the solar system. In this regard, the development of space radiation monitoring systems with the ability to evaluate radiation conditions in real time is extremely important. For practical applications, the established physical parameters of the fluxes of particles of GCR, ERB, and SCR and the laws of their variations are generalized using physical and mathematical models and are also an integral component of calculations in assessing radiation hazard. The report gave an overview of the current state of the problems of experimental research, monitoring and modeling of radiation fields in space, relevant for the implementation of long-term near-Earth and future space missions for the exploration of the Moon and Mars.

The report «X-ray and Gamma Radiation of Solar Flares» (D. D. Frederiks, A. L. Lysenko, D. S. Svinkin, M. V. Ulanov, A. E. Tsvetkova, R. L. Aptekar, A. F. Ioffe Physics and Technical Institute, St. Petersburg) was devoted to a brief review of recent results on the observation of solar flares in the hard X-ray and gamma-ray ranges. They are especially important for the diagnosis of accelerated particles, since it is in them that the bremsstrahlung of non-thermal electrons and gamma lines from nuclear reactions of accelerated ions are observed. Particle acceleration and plasma heating processes are typical of many astrophysical objects, and the Sun, the closest star to us, is a unique natural laboratory where they can be studied with unique spatial and temporal resolution.


Фотография солнечной вспышки X9.3, полученная космическим телескопом AIA на спутнике SDO

Although significant progress has been made in understanding the morphology of solar flares in the last decade, however, many unresolved issues remain in their physics, including, for example, elucidating the specific mechanisms of particle acceleration and the problem of heating the solar corona, whose temperature is orders of magnitude higher than the temperature photosphere.

The results obtained by the A. F. Ioffe Physics and Technical Institute of RAS during a joint Russian-American space experiment «Cone-Wind», which carries out continuous monitoring of flare solar activity in the range of 20 keV –15 MeV, since November 1994. The equipment of the experiment «Cone» consists of two scintillation gamma-spectrometer. They are mounted on the Wind satellite, stabilized by rotation in such a way that they constantly examine the entire celestial sphere. The satellite"s orbit is located completely in interplanetary space (at the so-called libration point L1, about 1.5 million kilometers from the Earth on the Earth-Sun line), i. e., outside the Earth"s radiation belts, which are dangerous for detectors. Also, thanks to this, the Earth does not close the detectors with an overview of any parts of the celestial sphere. An important objective of the experiment is to determine the coordinates of gamma-ray burst sources using the triangulation method according to the InterPlanetary Network (IPN) satellite with gamma-ray detectors on board.

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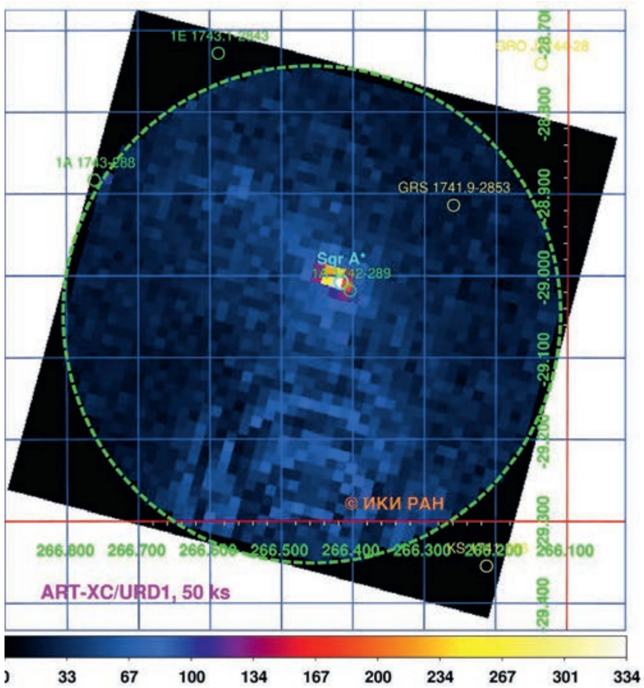
УСПЕШНЫЙ ЗАПУСК АСТРОФИЗИЧЕСКОЙ ОБСЕРВАТОРИИ «СПЕКТР-РГ»

С космодрома Байконур 13 июля 2019 года состоялся успешный пуск ракеты-носителя Протон-М» с разгонным блоком «ДМ-03» и космической астрофизической обсерваторией «Спектр-РГ». Космический аппарат «Спектр-РГ» создан в рамках Федеральной космической программы России по заказу Российской академии наук с участием Германии. Обсерватория оснащена двумя уникальными рентгеновскими зеркальными телескопами: ART-XC (производства ИКИ РАН, Россия) и eROSITA (MPE, Германия), работающими по принципу рентгеновской оптики косого падения. Телескопы установлены на космической платформе «Навигатор» (НПО Лавочкина, Россия), адаптированной под задачи проекта. Научный руководитель миссии – академик Рашид Алиевич Сюняев; научный руководитель по телескопу ART-XC (Россия) – д.ф.-м.н. Михаил Павлинский; научный руководитель по телескопу eROSITA (Германия) – Dr. Петер Предель.

«Спектр-РГ» будет работать в точке Лагранжа L2, которая находится примерно в 1,5 миллиона километров от Земли. Прибытие и выход на рабочую орбиту вокруг L2 запланированы на 21 октября 2019 года.



Второй телескоп проекта eROSITA передал первое рентгеновское изображение 27 августа 2019 года.

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