Millimetron: the next step of FIR Astronomy

A. Smirnov[1*], Th. de Graauw[1], A. Baryshev[2,3], P. de Bernardis[4], S. Likhachev[1],

D. Radchenko[1], S. Pilipenko[1] and N. Kardashev[1] on behalf of the Millimetron team

[1]*Astro Space Center of P.N. Lebedev Physical Institute, Moscow, Russia*

[2]*SRON Netherlands Institute for Space Research, Groningen, the Netherlands*

[3]*University of Groningen, Kapteyn Astronomical Institute, Groningen, the Netherlands*

[4]*Sapienza University of Rome, Rome, Italy*

*Contact: asmirn@asc.rssi.ru, phone +7-495-424-63-33

Abstract— **Millimetron is a space observatory dedicated to astronomical observations in an extensive range from mm to far infrared based on the use of a 10-m actively cold (< 10K) telescope. The telescope is a lightweight Cassegrain with a deployable on-orbit and active segmented primary mirror. The observatory will have four type of instruments: a far infrared instrument do both imaging and spectroscopy from 20 < λ < 450µm, a low resolution imaging spectropolarimeter from 300 < λ < 3000µm, an array spectrometer for high resolution far infrared spectroscopy from 50 < λ < 600µm and a heterodyne receivers for space-earth VLBI system. The observatory will be launched in the middle of next decade into orbit around the second Earth-Sun Lagrange point.**

A large collecting area and state-of-the-art instrumentations on-board of the observatory will enable unique observations in spectral range of great importance for astronomy. These observations will allow researchers to find answer to several key questions, which are related to the formation of stars and planets, galaxies and the interstellar medium, studies of black holes and others. We will show the predicted performance, the development status and the future prospect.

I. INTRODUCTION

The interest of astronomers to the submillimeter and far infrared bands is explained by the following:

- the maximum of radiation of coldest objects in the Universe, including dust clouds, asteroids, comets, is located in these bands;
- enable to study an extremely weak objects, because the minimum of the sky brightness is located near 300µm;
- there are very interesting for the atomic and molecular spectroscopy;
- the medium is more transparent than in the radio, near infrared and optics;
- this is the one of the possibilities which can significant increase of the angular resolution.

However, the observations in these bands still remains mostly unexplored, because are very technically demanding and attenuation of the Earth atmosphere which is practically opaque at wavelengths shorter than 300µm. Since the previous successfully launched space infrared observatories such as ISO[1], IRAS[2], Spitzer[3], AKARI[4] the recent progress in observations in submm/FIR is connected with the Herschel space telescope [5] and ALMA observatory (http://www.almaobservatory.org). The results of Herschel has brought a lot of new knowledge on the mechanism of star formation, the properties of the interstellar medium in our and other galaxies, the atmospheres of bodies of the Solar System, etc. However, the limited angular resolution and sensitivity of Herschel with 3.5-m primary mirror cooled only to 70K was insufficient for many important questions. These questions also cannot be solved by ground-based facilities of the near future, e.g. ALMA that has high angular resolution and sensitivity, but is limited by the Earth's atmosphere. Consequently, the next generation space missions open up inaccessible regions of the submm/FIR.

At the same time recent advances in the VLBI, namely the RadioAstron Space-VLBI mission [6], the Event Horizon Telescope (http://www.eventhorizontelescope.org/) allows to expect that with the mm/submm Space VLBI the horizon vicinity of black holes can be studied in great detail. These considerations lead to the concept of the Millimetron observatory.

II. SCIENCE DRIVERS

Millimetron space observatory is designed as fruitful astronomical instrument, which will be capable to meet the demands of astronomers in various fields. A review of suggestions of scientific proposals for this observatory can be find in the [7], where briefly discuss only the few science cases, which are the most important and unique for this mission. The studies of the near Universe (the Solar System, our Galaxy and several nearby galaxies) with Millimetron will answer the questions of the distribution of the Hydrogen and water in the various objects, their dynamics and chemical composition. The studies of [CII] 158µm and HD 112 and 56µm spectral lines in the Inter Stellar Medium (ISM) will reveal the distribution of the hidden warm Hydrogen, which cannot be detected by other means. HD detection is also considered as the best way to measure the masses of protoplanetary disks [8]. These studies will require the high-resolution spectroscopy on frequencies up to 6 THz. One of the impressive results of Herschel telescope was the discovery of the fact that all the star formation takes place in the thin filaments [9]. However, the origin of these filaments, and, in particular, the role of the magnetic field in it is not clear up to date. Observation of polarization of filament emission with help of the Millimetron will shed light on this problem.

For the cosmology and the distant Universe, Millimetron will contribute significantly to the study of high redshift galaxies, filling the gap in the spectral coverage between ALMA and planned to launch James Webb Space Telescope (http://www.jwst.nasa.gov/). In particular, with the help of the medium resolution grating spectrometer Millimetron will be the only one observatory which can be study the most important [CII], [NII], [NIII], [OI], [OIII] spectral lines at redshifts $z \leq 5$ in the majority of galaxies which are too faint for ground-based telescopes. These lines are responsible for the rate of star formation and properties of the ISM distant galaxies. At higher redshifts Millimetron will search for HD and H_2 rotational transition emission lines, which will give invaluable information about properties of the Population III stars and metal-poor galaxies. Such observations will require from observatory extremely high sensitivity.

Deep far infrared images will allow to find many new interesting targets for the subsequent spectroscopy by Millimetron and for the study in other bands, e.g. by extremely large optical telescopes. Far infrared colors can be effectively used to select high redshift galaxies [10].

The high sensitivity spectrometry at CMB frequencies, 0.5-3mm, will provide unique information about the Sunyaev-Zel'dovich effect and for the first time will allow the high precision decomposition of thermal and kinetic contributions to the effect for a large sample of galaxy clusters [11]. This also allows testing the cosmological model and the fundamental predictions of physics and astrophysics [12].

In the interferometer mode, the main object of interest will be the black holes. The black hole itself is radiating nothing, but the adjacent material, which is being accreted or accelerated, is a source of radiation that is then lensed by the black hole. This lensing creates the so-called shadow. Measuring its size and shape is the straightforward way to confirm the existence of black holes (as objects predicted by the General Relativity). The shadows of known black holes are predicted to be extremely small: < 40μarcsec, that's why the very high angular resolution is needed.

III. Millimetron Design and Expected Performance

In order to achieve the high sensitivity and angular resolution which are required by mentioned scientific objectives which was indicated in previous section the telescope mirrors should be a big and cooled to the temperature less than 10K. The big mirror means that it should have the greatest possible aperture, but be however light and compact to be carried by a launch vehicle into orbit. The telescope with deployable primary mirror can only meet the latter requirement. The cooling of the telescope to several Kelvins allows reaching sensitivity limited by the natural sky background. The main parameters of the observatory are given in Table 1 and the concept is shown in Figure 1.

The large aperture telescope is crucial for Millimetron, since it allows not only increasing the resolution (as 1/D), but also to reduce the confusion limit created by the distant submillimeter galaxies, which constitute the Cosmic Infrared Background (CIB).

TABLE 1
Millimetron Mission Requirements

Aperture of the telescope	10m
Aperture ratio	f/7
The telescope wavefront error (RMS)	≤ 10μm (goal ≤5μm)
Telescope temperature	< 10K
Covering wavelength range	20μm ÷ 20mm
Modes of observation	single-dish or element SVLBI system
Total mass	≤ 6600kg
Orbit	L2
Life time	10 years (3-5 years cold phase)
Launch vehicle	Proton

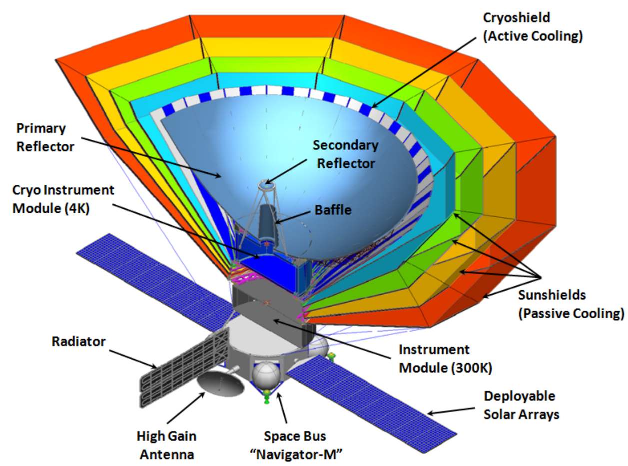

Fig. 1 The conceptual design of the Millimetron

Millimetron will resolve more than 90% of the Cosmic Infrared Background into individual sources at wavelengths up to 300μm [13]. The optical design of the telescope is a classical two-mirror Cassegrain system. Between the secondary mirror and focal plane is a third switching mirror. This mirror can be precisely and discretely rotated relative to the optical axis of the telescope and positioned to connect to various instruments. Cold space telescope requires minimization of the exterior thermal radiation. This justifies the short focus telescope design with the secondary mirror shielded by the deep primary mirror. The reflective surface of the primary mirror is formed by a central 3m solid dish, and 24 outer deployable petals unfolded on-orbit. Each Millimetron petals consist of three independent segments. Currently, the material of choice for the primary mirror is a high modulus carbon fiber, and a low temperature cyanate ester is supposed to be used as a binder.

For the Millimetron it is very important to achieve a high surface accuracy of the primary mirror after the deployment of the telescope in space. The deployment strategy is based on the previous successfully launched mission - RadioAstron, which has the same size and optimized for working in centimeter wavelengths. To achieve the required surface accuracy of the space telescope in the FIR, an active surface control system will be used to control all segments of the primary mirror with help of the wave-front sensing technique. This system will be periodically employed to correct inaccuracies in the positions of the deployed segments and variations of the overall surface caused by different factors.

The Millimetron spacecraft can be divided into two parts: the payload module and the bus module. We plan to use upgraded space bus module Navigator produced by the Lavochkin Association, Russia.

Launch services will be provided by Russia (Russian Space Agency) since the Millimetron mission is included in the Russian Federal Space Program. The total mass of the spacecraft is about 6.6 tons and launch vehicle Proton in combination with a booster, are fully satisfactory to carry the spacecraft into orbit.

As we indicated above, cooling is one of the critical issues for the Millimetron mission. To achieve the required sensitivity of the telescope in the submm/FIR we need to cool the entrance optics of the telescope (including antenna) and the focal plane instrument down to the temperature about 4.5K. It may be possible to do this on-orbit only by a combination of effective radiation cooling and additional mechanical cooling. The telescope will be cooled passively to a temperature about 30 – 60K by a suite of the deployable multi-layer V-groove shields. The closest to the primary mirror cryogenic shield should be cooled to about 20K by using 20-K class mechanical coolers. That step reduces the radiation loads going from previous shields to primary mirror which will have the lower temperature. The 4-K class mechanical coolers will be used to cool the antenna as well as the focal plane instruments. Typically, those coolers consist of two-stage Stirling coolers and Joule-Thomson coolers with He-4 as operating gas. Sensitive detectors for submm/FIR which will be placed in the instruments of the Millimetron require further deep cooling to temperatures about 50-300mK. These temperatures will be generated within the instrument (as in the Herschel PACS scheme). May be it requires to use a 1-K class cooler, which consists of two-stage Stirling cooler and Joule-Thomson cooler with He-3 as operating gas. The mission life time with the active cooling system is estimated to be 3 – 5 years and depending of mechanical coolers lifetime.

IV. Scientific instrumentation

As indicated before the mission is going to cover a very wide wavelength range of the spectrum from the millimetre to the FIR with a four focal plane instruments: MHIFI (Millimetron Heterodyne Instrument for the Far Infrared), SACS (Short wave Array Camera/Spectrometer), LACS (Long wave Array Camera/Spectrometer) and heterodyne receivers for SVLBI. The cold parts of all receivers will be installed within a cryogenic container in focal plane of the telescope.

The MHIFI is a successor of the Herschel HIFI instrument. It will cover higher frequencies, up to 6THz (50μm). A new approach for that type of instruments is a multi-pixel design. The mixer technology for the frequencies below 1 THz will be SIS (Superconductor-Insulator- Superconductor) and HEB (Hot Electron Bolometer) for the higher frequencies. We predicted sensitivity of the instrument about 5 quantum limits. The low frequency bands of the MHIFI (557-752 and 752-950 GHz) can be also used as SVLBI receivers. Up to day the many parts of the instrument has high technology readiness level (TRL).

The SACS will operate at wavelengths range 20-450μm. It will contain a grating spectrometer with medium spectral resolution (R ≈ 1000) and at the same time an imaging camera with up to thousand pixels and field of view 6x6 arcmin at > 2THz. The concept of spectrometer will be analogous to the BLISS instrument [14]. This instrument allows observing wide spectral range simultaneously with very high sensitivity. The required detector sensitivity in terms of Noise Equivalent Power (NEP) should be about 1×10^{-19}W/Hz$^{1/2}$ or less.

The LACS (spectropolarimeter) consists of a differential Fourier spectrometer for covering wavelengths from 0.3 to 3mm and several bands imaging camera with number of pixels in the range from 6 to 100. Since LACS works in the wavelength range where the CMB radiation (signal) plays dominated role, the requirements for sensitivity of the detectors for him can be relaxed to $10^{-18} \div 10^{-17}$ W/Hz$^{1/2}$.

The heterodyne receivers for SVLBI mode should cover bands of 1.35 cm (22 GHz) and ALMA bands 1 (33-50 GHz), 3 (84-119 GHz), 6 (211-275 GHz), and probably 9 (602-720 GHz) and 10 (787-950 GHz). The last two bands will be the parts of the MHIFI instrument, while the other bands will be separate instruments. For this observations mode we plan to use an on-board maser reference (hydrogen maser) and an on-board formatter with memory up 10TB. After preliminary on-board processing the high-speed down-link transmits the data to the ground for the further processing. All the receivers are sensitive to polarisation. The instantaneous bandwidth of all SVLBI receivers will be about 4 GHz per polarization. The limitation of this bandwidth today goes from the on-board memory volume and low data rates in communication channel.

V. Discussion of future prospect

Currently Millimetron is supported and approved by the Russian Space Agency. The telescope construction, mechanical design, the space bus module, the mirror technology, SVLBI receivers, sun shields and many other parts are now in the phase of development, verification and testing.

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