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Current tasks and prospects of millimeter and submillimeter astronomy [*]

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Contents

Abstract. **An overview of the main research areas, the most important results and current scientific problems of millimeter and submillimeter astronomy is presented. The prospects for the development of this area in the world and in the Russian Federation are discussed.**

Keywords: millimeter and submillimeter astronomy, radio telescopes, radio interferometers, atmospheric transparency

1. Introduction

The active development of millimeter-wave astronomy began in the 1960s, when the first large antennas in this range were built (such as the 11-meter radio telescope of the US National Radio Astronomy Observatory, the RT-22 PRAO, the RT-22 CrAO, and others) and sufficiently sensitive receivers were created. An overview of the initial stage of this field's development is given, for example, in the work [1]. In subsequent years, antenna and receiving technology for the millimeter range developed rapidly. The noise temperature of heterodyne receivers approached the so-called quantum limit, the existence of which follows from the energy–time uncertainty relation. New radio telescopes in this range were built, both single and antenna arrays. At the same time, there was a gradual advance into the region of ever shorter wavelengths — the submillimeter range, which borders on the infrared and, in fact, overlaps with it, since it is often called the far infrared. Terahertz and subterahertz terminology is also used. Further progress in millimeter and submillimeter astronomy is described, for example, in reviews by [2, 3].

Figure 1. Researchers from NIRFI conduct radio astronomical observations in the 1 mm wavelength range in the Tien Shan (at the SAI observatory; 1975).

In the USSR, the first observations of astronomical objects and atmospheric transparency studies in the submillimeter wavelength range were conducted using small antennas in the Pamir and Tien Shan mountains by researchers from the Radiophysical Research Institute (NIRFI) under the leadership of A.G. Kislyakov (Fig. 1) and the Space Research Institute (IKI) of the USSR Academy of Sciences (G.B. Sholomitsky et al.).

The placement of submillimeter-wavelength telescopes in mountains is dictated by the strong absorption of radiation in this range by atmospheric gases, primarily water vapor and oxygen. Figure 2 shows a graph of the atmospheric transmittance at the Atacama Large Millimeter/submillimeter Array (ALMA) site in the high-altitude Atacama Desert (5000 m) in Chile, plotted against the amount of precipitable water vapor in the atmosphere. This quantity is defined as the integral over

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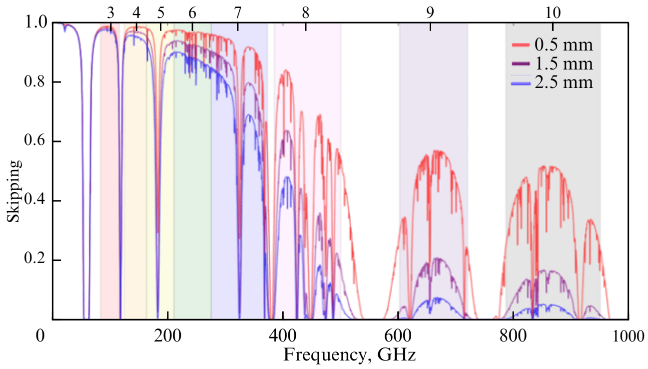

Figure 2. Atmospheric transparency in millimeter and submillimeter wavelengths in the Atacama Desert, Chile, at an altitude of 5000 m above sea level, as a function of the amount of precipitable water vapor in the atmosphere. ALMA's operating ranges are shown. ©ALMA (ESO/NAOJ/NRAO).

height of the volume density of water vapor, normalized by the specific weight of water, which corresponds to the thickness of the water layer that would result if all the water vapor in the atmosphere above a given location were to condense on the surface. It is usually measured in millimeters.

Observations from the Earth's surface are only possible in so-called atmospheric transparency windows — frequency ranges with acceptable transparency between strong water vapor and oxygen absorption lines. At frequencies $\gtrsim 1.5$ THz, such windows in the submillimeter range are virtually nonexistent.Therefore, measurements were conducted using balloons, the airborne observatory SOFIA (Stratospheric Observatory for Infrared Astronomy; its operation ceased in 2022) [4] was in operation, and space observatories were created, the largest and most effective of which is the European Space Agency's 3.5-meter Herschel telescope [5], which operated successfully from 2009 to 2013. In the 2030s, the launch of the Russian Millimetron space observatory with a 10-meter antenna is planned, which will significantly exceed the capabilities of the Herschel observatory [6, 7].

Millimeter and submillimeter astronomy plays a key role in several areas of research. First, it is the study of what can be called the 'cold' Universe. These are primarily dense interstellar clouds of gas and dust, both in our Galaxy and beyond. These clouds are the sites of star formation, many aspects of which are still not fully understood. The temperature of interstellar clouds ranges from a few to tens of Kelvins. At this temperature, their emission peak lies in the submillimeter range. This range is also very rich in spectral lines, primarily corresponding to transitions between rotational levels of molecules with relatively low excitation energies. To date, approximately 330 different molecules, not counting isotopologues, have been detected in interstellar and circumstellar clouds.[1] Observations of these molecules' lines provide unique information about the physical conditions in interstellar clouds, their structure and kinematics, as well as their chemical composition.

Studies of the microwave background (CMB), whose temperature is approximately 2.73 K, also fall into this category. The spectrum, anisotropy, and polarization of the background are investigated. The problems encountered here are discussed below.

Another class of problems where millimeter and submillimeter astronomy plays a key role is the study of distant astronomical objects with very high angular resolution using very-long-baseline radio interferometry. Clearly, higher resolution can be achieved at shorter wavelengths with the same baseline length. Furthermore, it is important to note that scattering in the interstellar medium in this range decreases with shorter wavelength. This allowed us to obtain images of supermassive black holes in the galaxy M87 and at the center of our own galaxy [8–10] at a wavelength of 1.3 mm using the so-called Event Horizon Telescope (EHT), which unites the largest telescopes operating in this range (approximately 10 telescopes).

Impressive advances in millimeter and submillimeter astronomy raise new questions and stimulate further development of instrumentation in this range. Below, we consider the current challenges of this area of research and its prospects for development.

2. Main results and current tasks of millimeter and submillimeter astronomy

2.1 Microwave background radiation

By now, it has been established that the spectrum of the microwave background is very close to the blackbody spectrum. No deviations have yet been detected. Such deviations may be caused by energy release processes in the early Universe [11]. The nature of the spectrum distortions depends on the epoch in which the energy release occurs (e.g., [7]). At redshifts $5 \times 10^4 < z < 2 \times 10^6$, so-called μ-distortions arise, which correspond to a nonzero chemical potential μ. When energy is released at later epochs, up to $z \sim 10^3$, the spectrum distortions correspond to the Sunyaev–Zeldovich effect and are called y-distortions, in accordance with the generally accepted notation for the photon Comptonization parameter in electron plasma. Similar distortions can also arise at later epochs during the formation of large-scale structure. The relative amplitude of these distortions is very small, $\lesssim 10^{-4}$.

The background spectrum can also be influenced by dust and molecules in the early Universe [12–15]. Simple molecules such as H_2, HD, HeH^+, and LiH could have been formed in noticeable amounts soon after the recombination epoch [16, 17]. Features in the background spectrum caused by these molecules can arise from resonant scattering of background photons by proto-objects moving at significant velocities relative to the microwave background [16, 18]. Heating of gas in collapsing primordial density perturbations is also possible. Thus, observations of such spectral distortions can be used to study the formation of primary structures in the so-called 'Dark Ages' of the Universe — the period between the recombination era and the appearance of the first stars. Several unsuccessful attempts have been made to search for such spectral features, including at millimeter and submillimeter wavelengths [19, 20]. In the paper [21], an attempt was made to search for the $J = 1-0$ HeH^+ line in the spectrum of a distant quasar ($z = 6.42$). The line was not reliably detected.

Dust could have appeared after the formation of the first stars. Therefore, studying the distortions of the background spectrum caused by dust is important for studying the history of star formation in the early Universe. The JWST results show that this component raises many questions. The dust

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[1] https://cdms.astro.uni-koeln.de/classic/molecules.

content of galaxies at high redshifts is discussed, for example, in the paper [22].

One of the most important tasks in studying the Universe is searching for manifestations of primordial gravitational waves, which arise in inflationary models in the first moments of its life. The only observational manifestation of these waves, as currently believed, is the B-mode polarization of the microwave background [23]. In addition to primordial gravitational waves, the B-mode can arise from gravitational lensing and scattering by dust in the Galaxy. This component has been measured in a number of experiments [24]. However, searching for radiation with such polarization caused by primordial gravitational waves remains a crucial task. Its discovery was reported several years ago [25], but data from the Planck spacecraft showed that this signal was due to dust in our Galaxy.

2.2 Galaxies and galaxy clusters

2.2.1 Active galactic nuclei and supermassive black holes. One of the most striking achievements of millimeter-wave astronomy was the aforementioned observations of supermassive black holes (SMBHs) in the galaxy M87 and at the center of our own galaxy [8–10], at a wavelength of 1.3 mm using the aforementioned Event Horizon Telescope (EHT). Further studies of these objects require a significant increase in angular resolution, which can be achieved using ground-based and space-based facilities in the Millimetron project. A detailed discussion of the scientific objectives of such research is presented in [7]. Increasing angular resolution will also make it possible to study several other SMBHs.

Besides SMBHs, high-resolution observations allow us to study active galactic nuclei (AGNs) and the relativistic jets that arise in these objects. A key advantage of the millimeter-wave range is the absence of synchrotron absorption, which allows us to study the central regions of AGNs. In particular, it is proposed to use the next-generation EHT to study the central regions of blazars [26], which are likely sources of high-energy neutrinos [27, 28].

Observations of (sub)millimeter H_2O megamasers in distant galaxies have significant potential [29]. Such observations allow for highly accurate estimation of the masses of central objects and the study of, for example, the growth of SMBH masses in galaxies. In AGN research, studying their variability is of great importance.Multi-frequency monitoring of hundreds of AGNs, particularly blazars, has long been performed with the RATAN-600 (e.g., [30–32]). However, this monitoring does not include millimeter-wavelength monitoring. Monitoring in the 8-mm wavelength range is conducted with the RT-22 at the Crimean Astrophysical Observatory (e.g., [33]).

There are also examples of AGN monitoring at short millimeter wavelengths. For example, the POLAMI (Polarimetric Monitoring of AGN at Millimetre Wavelengths) project is being implemented at the 30-m IRAM radio telescope, within the framework of which all four Stokes parameters are monitored at wavelengths of 3 mm and 1.3 mm for a sample of 37 AGN [34, 35].

2.2.2 Submillimeter and bright infrared galaxies. Submillimeter sky surveys have revealed a significant number of galaxies that are very bright in the submillimeter wavelength range [36]. They are commonly called submillimeter galaxies. Submillimeter radiation is generated by heated dust, and the high luminosity at these wavelengths may be due to a burst of star formation, which can be caused by galaxy mergers. However, apparently, high rates of star formation are not always due to this factor (e.g. [37]). Most submillimeter galaxies are located at redshifts $z \sim 2-4$ and the peak of their emission, located in their own reference frame at wavelengths ~ 100 μm, shifts correspondingly to longer wavelengths. Submillimeter galaxies, together with bright IR galaxies, form a class of dusty starforming galaxies (DSFG; [38]). Further study of these objects is an important and pressing task in submillimeter astronomy.

2.2.3 Sunyaev–Zeldovich effect. An interesting and important application of millimeter and submillimeter waves in astrophysics is the Sunyaev–Zel'dovich effect (SZE), a weak distortion of the microwave background spectrum due to the scattering of background photons by high-energy electrons [39]. Large numbers of these electrons are present in the centers of galaxy clusters. The thermal SZE manifests itself as a decrease in the CMB intensity at frequencies below 218 GHz and an increase at higher frequencies. The magnitude of this effect is independent of redshift, allowing the detection of very distant galaxy clusters. For example, using the 6-meter Atacama Cosmology Telescope (ACT) in Chile, a catalog of more than 4000 galaxy clusters was compiled using SZE observations at wavelengths of 3 and 2 mm [40]. The 10-meter South Pole Telescope (SPT) at the South Pole conducted a deep survey of a 100-square-degree area in the 3, 2, and 1.3 mm wavelength ranges, identifying approximately 500 candidate galaxy clusters [41]. Further studies of this effect, including at submillimeter wavelengths, are warranted. Such observations should, in particular, allow us to determine the temperature of relativistic electrons [42].

The electrons in typical galaxy clusters should be relativistic.In addition to thermal SZE, kinematic SZE is also possible, related to the motion of objects relative to the cosmic microwave background. This effect was first observed in [43] and has been observed in several other studies. It was recently studied in detail by combining observational data from a large number of galaxies [44, 45]. These results are of great importance for understanding galaxy formation processes. Significant progress in research on this effect is expected.

2.3 Interstellar medium, formation of stars and planets

2.3.1 Interstellar medium and star formation. The interstellar medium is multicomponent. Observations at millimeter and submillimeter wavelengths allow us to study relatively dense and cool regions where star formation processes occur. Studies of the general characteristics of such regions are based on surveys in the continuum and in molecular spectral lines at wavelengths from millimeter to infrared. Quite a few such surveys have been completed to date.A good example is the CO $J = 1-0$ line survey of the galactic plane [46], which served as the basis for many subsequent studies. Such a survey provides a general understanding of the distribution and kinematics of interstellar matter. More recently, ground-based and space-based instruments have been used to survey large regions of the galactic plane with significantly higher resolution in the continuum and in the lines of certain molecules. Among them, we can note the ground-based continuum surveys at ~ 1 mm wavelengths ATLASGAL (The APEX telescope large area survey of the galaxy at 870 μm) [47, 48] and BOLOCAM [49], as well as a survey in the ^{13}CO $J = 1-0$ line GRS (The Boston University-Five

College Radio Astronomy Observatory Galactic Ring Survey) [50]. A great deal of useful information was provided by spacecraft operating at wavelengths from the far IR to the near IR ranges (for example, *Spitzer* Galactic Legacy Infrared Mid-Plane Survey Extraordinaire — GLIMPSE [51] and MIPS Inner Galactic Plane Survey — MIPSGAL [52], *Herschel* [5] infrared Galactic Plane Survey — Hi-GAL [53], Wide Field Infrared Survey Explorer — WISE [54]). The results of these surveys are now actively used in the study of star-forming regions.

Another type of similar work is surveys of samples of objects selected according to various criteria, which may represent different types of star-forming regions or may be indicators of such regions. Surveys are carried out in the continuum at millimeter and submillimeter waves, as well as in the lines of common molecules such as CO, CS, NH_3, HCN, HCO^+, N_2H^+ and some others. A bright example of such studies is a series of works by Philip Myers and coauthors on the study of dense cores in dark clouds, carried out quite a long time ago [55–70]. As a result of this work, the main physical characteristics of such cores were determined, the chemical composition was investigated, and correlations between parameters were studied.

In these dark clouds, low-mass stars, on the order of the Sun's mass and smaller, are formed. Similar work has been and is being conducted in the direction of the regions of formation of massive stars (stars with masses of $M \gtrsim 8\,M_\odot$). The process of formation of massive stars appears to be more complex than the formation of low-mass stars and still has many unclear points (e.g., [71, 72]), related to the fact that nuclear reactions in massive protostars begin much earlier than they gain their final mass. Radiation pressure can stop further influx of matter. It is also not entirely clear how to explain the fact that massive cores do not disintegrate into smaller fragments. Studies of the regions of high-mass star formation are complicated by the fact that they are located much further from us than the dark clouds in which low-mass stars are formed. The nearest such region is at a distance of ~ 500 pc, and typical distances are several kiloparsecs. Interferometers are required for their detailed study. Currently, there is no generally accepted model for the formation of massive stars. Several main possible scenarios exist, the applicability of which is currently being actively studied. Therefore, studying the formation of massive stars remains one of the most pressing problems in astrophysics and should be addressed primarily by millimeter and submillimeter astronomy. A review of observational studies in these areas is presented in the paper [73].

Among the many works on this topic, we note a series of our studies, begun in the 1980s at the RT-22 CrAO [74–76] and then continued at various instruments around the world [77–88]. In these studies, surveys of several dozen regions of the formation of massive stars were carried out in the lines of such molecules as HCN, HCO^+, CS, NH_3, N_2H^+, HNCO, $C^{18}O$, SO, and others. This made it possible to obtain statistical distributions of the main physical parameters for these objects, in particular, size, mass, density, and velocity dispersion. Based on observations of NH_3 and CH_3CCH, estimates of the kinetic temperature of the gas were made [81, 89, 90].

Studies of star-forming regions revealed that virtually all interstellar clouds have a filamentary structure. Furthermore, it was found that the filaments are the primary sites of star formation [91]. The characteristics of these filaments are currently being actively studied through observations of dust and molecular emission at millimeter and submillimeter wavelengths. Theoretical models of the formation and evolution of such structures are being developed. Observations show that in some cases, star formation occurs more rapidly at the ends of the filaments [92–94], which may be due to the acceleration of matter in these regions [95]. In many cases, the most active star formation is observed at the intersections of the filaments. There are indications that this process may be initiated by filament collisions (e.g., [96–98]). Numerous studies indicate that filaments arise naturally as a result of supersonic turbulence and shock wave action (e.g., [91, 99]. They can also arise from the fragmentation of flat structures (e.g., shells around H II regions, old supernova remnants, etc.). Research into interstellar filaments will be relevant for quite some time to come.

Ultimately, star formation occurs in so-called dense cores, which can form, for example, as a result of the fragmentation of interstellar filaments. Currently, a specific classification of such cores has been developed, based on data on the presence of (proto)stellar objects within them and their spectral characteristics. This classification has been developed most thoroughly for cores in low-mass star formation regions. They are conventionally divided into several main categories: starless, pre-stellar, and protostellar [100]. Pre-stellar cores, unlike starless, are gravitationally bound and can subsequently form a protostar. In protostellar cores, such a protostar already exists. Protostellar cores are conventionally divided into four classes — from Class 0 to Class III — based on their spectral characteristics and apparently corresponding to the evolutionary sequence [101–103].

Much effort has been devoted to searching for massive prestellar cores (with a mass of $\sim 30\,M_\odot$ within a radius of 0.03 pc) that could form a massive protostar. The discovery of such cores could support the monolithic collapse model for the formation of massive stars. To date, only a few candidates for such cores have been discovered [104]. The lack of a significant number of massive prestellar cores may be explained by their short lifetimes, on the order of the free-fall time.

It is now generally accepted that the formation of stars with solar masses occurs through disk accretion accompanied by bipolar outflows. Numerous disks have been observed in regions where low-mass stars form. Discs or toroidal structures have also been observed around several dozen massive protostars [105]. High-velocity bipolar outflows are observed ubiquitously. A detailed review of their characteristics and models is presented in [106]. Of particular interest are observations of disks and outflows in regions where massive stars form, as they provide insight into the formation mechanism of such stars.

Recently, events have been detected that support episodic disk accretion as a mechanism for the formation of stars with masses up to at least $\sim 20\,M_\odot$. The first to be observed were luminosity outbursts from the objects NGC6334I-MM1 [107] and S255 NIRS3 [108, 109]. They were accompanied by bursts of maser emission [110–113]. These events were interpreted as the result of episodic accretion of matter onto the central massive protostar, similar to that observed during the formation of low-mass stars but on a much larger scale. This roughly corresponds to some theoretical models of fragmented disks around massive protostars [114]. Such phenomena have now been detected in several objects [115], and it is clear that research into such episodic accretion in massive protostars is highly relevant and will be actively pursued.

One of the most important current tasks is the study of star formation in the early Universe. This issue is discussed in the review [7].

2.3.2 Interstellar molecules. One of the important and rather unexpected results of radio astronomy studies of the interstellar medium has been the discovery of a large number of different molecules. These molecules are primarily discovered through observations of their spectral lines at millimeter and submillimeter wavelengths. As noted above, over 300 different molecules, not counting isotopologues, have been discovered to date. Among them are many complex organic molecules. There have been unconfirmed reports of the detection of the simplest amino acid, glycine. These discoveries have stimulated the development of models for the chemical evolution of the interstellar medium. Future research is largely aimed at identifying compounds that may be associated with biological evolution. Notable projects include the PRIMOS (PRebiotic Interstellar MOlecule Survey) project, carried out on the GBT radio telescope, and the SOLIS (Seeds Of Life In Space) project, implemented on the IRAM NOEMA interferometer. Related to this line of research are observations of water molecules, particularly in protoplanetary disks. The presence of water is essential for the existence of life as we know it. The search for and study of complex molecules and water in the universe are discussed in detail in the works [7, 116].

One important area of research is the study of deuterium fractionation in interstellar clouds. This effect is due to the exothermic nature of the proton-deuteron exchange reactions in molecules, which underlie the chains of chemical reactions leading to the formation of most other molecules (e.g., [117]). It has been studied primarily in dark, cool clouds, but recently it has been found that deuterium fractionation also occurs effectively in warm clouds where massive stars are born. In particular, we surveyed several dozen regions of massive star formation using the lines of a number of deuterated molecules in the 3–4 mm wavelength range using the 20-m radio telescope at the Onsala Observatory. The results of observations of DCN, DNC, DCO^+, N_2D^+ and NH_2D were published in the papers [118, 119]. Deuterated molecules were detected in approximately one-third of the observed objects. Differences in the dependences of the relative abundance of such molecules on temperature and velocity dispersion were revealed. Further observations with the 30-m IRAM radio telescope made it possible to study the spatial variations in the degree of deuterium enrichment for different molecules, as well as to evaluate the physical characteristics of the sources [120, 121].

2.3.3 Search for variations in fundamental physical constants based on observations of molecular clouds in our and other galaxies. The question of whether fundamental dimensionless physical constants are truly constant or can vary in space and time requires study, and a considerable amount of work has been devoted to this type of research. These studies are based on measurements of the relative shifts of the spectral lines of atoms and molecules, the frequencies of which depend differently on these constants (e.g., [122]; A.V. Lapinov et al. *Vestnik RFBR* 1(73) 111–118 (2012)). The highest measurement accuracy can be achieved in the microwave range, including millimeter and submillimeter waves, when studying possible spatial variations of fundamental constants in the Galaxy. The possibility of such variations appears in models of so-called chameleon scalar fields (e.g., [123]), which assume that the potential and effective mass of a scalar field quantum are modulated by the local density of matter. In this case, fundamental dimensionless constants such as the fine structure constant, $\alpha \approx 1/137$, and the electron-to-proton mass ratio $\mu = m_e/m_p$ become dependent on the local density. Theoretical models predict that relative variations in μ should significantly exceed variations in α, so current research is aimed specifically at searching for variations in the electron-to-proton mass ratio.

For this purpose, observations and analysis of observational data of cold molecular clouds in the Galaxy with low velocity dispersion in the lines of a number of molecules were carried out, primarily NH_3, HC_3N and CH_3OH [124–132]. Inversion transitions of NH_3 and rotational transitions of HC_3N have different sensitivities to the value of μ. Different types of transitions of methanol CH_3OH also have different sensitivities. These observations yield an upper limit on the variations of $|\Delta\mu|/\mu \lesssim 3 \times 10^{-8}$, although recent studies [131, 132] have found indications that in the molecular clouds of the Galactic center, this ratio is lower than laboratory measurements and nearby molecular clouds by $\sim (3-4) \times 10^{-7}$ ($\sim 5\sigma$).

These studies require very high-precision knowledge of the transition frequencies. For most molecules, the current accuracy is insufficient. Precision laboratory measurements of these frequencies are required. For this purpose, sub-Doppler spectrometers based on Lamb dip measurements were developed at the IAP RAS [133, 134]. Overall, this line of research has promising prospects.

It's worth noting that precision measurements of the frequencies of various transitions in various molecules are also important for studying the kinematics of cold clouds with low velocity dispersion, since different transitions trace different regions within such a cloud.

2.3.4 Protoplanetary disks and exoplanets. In recent years, ALMA has provided the first detailed images of a number of protoplanetary disks (for example, [135]), significantly expanding our ability to study planet formation processes.

Using ALMA, astronomers have confidently detected a dust disk around an extrasolar planet for the first time [135]. These observations shed light on the mechanisms of moon and planet formation in young stellar systems. These studies are just beginning and hold great promise, based on a combination of observations in the millimeter/submillimeter and other wavelength ranges.

2.4 Solar system

ALMA allows for millimeter-wavelength imaging of the solar surface, particularly sunspots, with record-breaking angular resolution. This enables detailed investigation of the magnetic field structure in active regions. An important objective is to study the nature of the sub-terahertz component of solar flare radiation [136].

Observations of molecular spectral lines at millimeter and submillimeter wavelengths allow for the study of the chemical composition of the atmospheres of planets and their satellites, as well as the composition of gases evaporating from the surfaces of comets as they approach the Sun. High-angular-resolution observations allow for the study of atmospheric mass movements, the kinematics of comet tails, and other related fields. These tasks will remain relevant for a long time. They include studying the isotopic composition of water and other compounds and determining the ratio of deuterium to hydrogen abundances.

Of particular interest is the search for compounds that may serve as indicators of biological evolution. In this regard, the work [137] is noteworthy, which reported the detection of phosphine on Venus using millimeter-wavelength observations with ALMA and JMCT, in quantities that cannot be explained by sources other than biological ones. This work has been heavily criticized, so its results are currently considered inconclusive, but this is a very interesting line of research and will obviously develop further.

3. Prospects for millimeter and submillimeter astronomy

The achievements of millimeter and submillimeter astronomy, partially described above, and the existence of important current problems stimulate further development of this field. Since the atmosphere greatly limits the possibilities of observations at these wavelengths, space projects are being implemented. As noted above, the European Space Agency's Herschel space observatory, which operated at the L2 Lagrange point from 2009 to 2013 [5], was very successful. The Astrospace Center (ASC) of the Lebedev Physical Institute (LPI) is currently implementing a project for the Russian space observatory 'Millimetron' with a cooled antenna 10 m in diameter [6, 7]. It is planned that this facility will operate both as a single-dish antenna, which will significantly exceed the capabilities of Herschel, and as a ground-space interferometer. The launch of this observatory is planned for the 2030s.NASA is also considering a project for a space-based submillimeter telescope ($\sim 3-600$ μm) with a large (9.1 or 5.9 m) mirror cooled to ~ 4 K (Origins Space Telescope [138]), but it does not include a VLBI mode.

The ASC LPI is also considering projects for a subterahertz space interferometer consisting of several antennas, as well as an antenna array on the lunar surface [139, 140].

Such space projects are undoubtedly important, as they allow them to solve problems that cannot be solved using ground-based instruments. However, the cost of these projects is quite high, and the active operating time of such spacecraft is quite limited. At the same time, many of the relevant problems listed above can be successfully solved using ground-based instruments. Ground-based antennas are also needed to support the ground-space interferometer. Several ground-based millimeter and submillimeter telescope projects, both single-dish antennas and interferometers, are currently at various stages of development and implementation.

The largest single-dish millimeter telescope currently in operation is the 50-meter-diameter Large Millimeter Telescope (LMT) Alfonso Serrano in Mexico [141] (Fig. 3). A surface accuracy (standard deviation) of approximately 100 μm has been achieved there, slightly higher than the target of 75 μm. Nevertheless, this provides an acceptable aperture efficiency (η_{A}) of $\sim 30\%$ at a wavelength of 1.3 mm, making it suitable for the Event Horizon Telescope project.

Currently, the world's primary submillimeter-wave instrument is the Atacama Large Millimeter/submillimeter Array (ALMA), which consists of 54 12-m and 12 7-m antennas in the high-altitude Atacama Desert (5000 m altitude) in Chile (Fig. 4). The maximum distance between antennas is 16 km. This is an international project involving many countries and organizations.

Figure 3. The Large Millimeter Telescope Alfonso Serrano, 50 m in diameter, is located on the summit of the Sierra Negra (4,600 m above sea level) in Mexico. ©LMT.

Figure 4. The Atacama Large Millimeter/submillimeter Array (ALMA). ©ALMA (ESO/NAOJ/NRAO).

The modernization of the IRAM millimeter interferometer in the Alps, now called NOEMA (NOrthern Extended Millimeter Array; Fig. 5), has been completed. The number of 15-meter antennas has been doubled, reaching 12. The interferometer's baseline length now reaches 1.7 km (in the east–west direction).

Existing millimeter and submillimeter instruments have high resolution but a relatively small field of view, which limits their capabilities, particularly in the study of extended areas. In this regard, projects to create large submillimeter telescopes with a large field of view, which could accommodate array receivers with a very large number of elements, are being actively discussed (and implemented). The most ambitious project is The Atacama Large Aperture Submillimeter Telescope (AtLAST) — a radio telescope with a diameter of ~ 50 m, an operating range of up to ~ 1 THz and a field of view of $\sim 2°$ [142]. In terms of throughput (the product of the effective area and the field of view), it will have

Figure 5. The NOerthern Extended Millimeter Array (NOEMA) millimeter interferometer of the Institute for Millimeter Astronomy (IRAM) in the Alps at an altitude of 2560 m. ©IRAM.

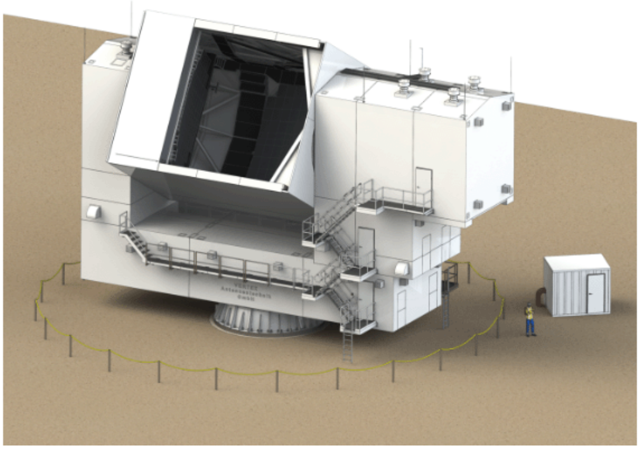

Figure 6. The Fred Young Submillimeter Telescope (FYST; formerly CCAT-prime) has a diameter of 6 m and a field of view of ~ 8°. It is located at an altitude of 5600 m in the Atacama Desert in Chile. ©FYST.

no equal. AtLAST's key scientific objectives include surveys of the galactic plane, studies of hidden components of the circumgalactic medium, submillimeter extragalactic surveys similar to SDSS, and high-resolution studies of the Sunyaev–Zel'dovich effect in galaxies and galaxy clusters.

The AtLAST project is still under discussion. However, a smaller telescope with approximately the same throughput has already been completed. This is the Fred Young Submillimeter Telescope (FYST, formerly CCAT-prime; Fig. 6) [143]. With a significantly smaller diameter (6 m), it has a field of view of ~ 8°. The telescope has already been delivered to its designated site at an altitude of 5600 m in the Atacama Desert in Chile. 'First light' is expected in 2026. This telescope is equipped with bolometric modules for the ranges from 1.3 mm to 350 μm with a large number of elements (~ 40,000 at 350 μm [144]), as well as 8 × 8 element matrix heterodyne receivers for the bands of 650 μm and 350 μm [145].

The well-known project to build a 70-meter millimeter-wave radio telescope on the Suffa Plateau in Uzbekistan [146, 147] also envisions a large field of view. However, the prospects for this project's implementation are still unclear. Options for constructing a smaller-diameter antenna at this site, which could operate in a VLBI network, or an array of smaller antennas are being discussed. Potential applications for these are discussed in [148].

The success of the Event Horizon Telescope project is fueling plans for a significant expansion of this system [149].

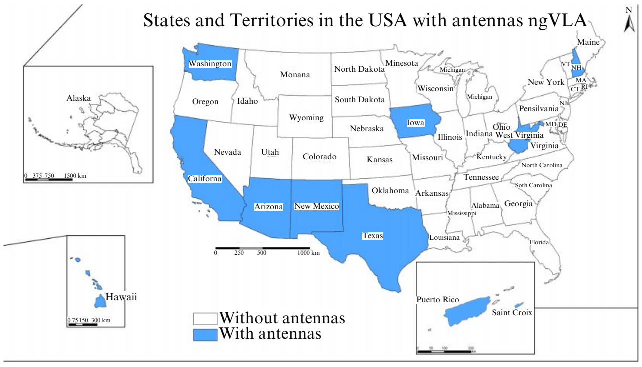

Figure 7. Planned locations of the antennas of the Next Generation Very Large Array (ngVLA). ©NRAO.

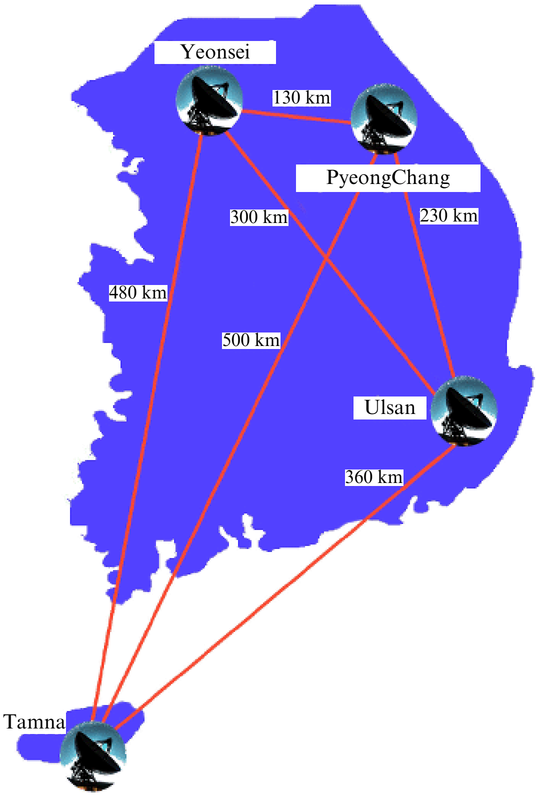

Figure 8. Locations of antennas of the Korean VLBI network operating in the millimeter-wave range (KVN). ©KVN.

Atmospheric conditions are being analyzed at several dozen potential antenna sites that could participate in the project's measurements [150]. Assessments indicate that a significant number of them are quite suitable for this purpose.

One of the most effective radio astronomy instruments is the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) in the United States. It operates at frequencies up to ~ 50 GHz. The Next-Generation VLA (ngVLA [151]) project envisions the construction of 244 18-m antennas over a significant portion of the United States (Fig. 7). The operating range of this system will be from 1.2 to 116 GHz.

The Korean VLBI network (KVN), operating in the millimeter-wave range, was recently expanded. It now consists of four antennas with a diameter of 21 meters. The surface accuracy of the latest, recently installed antenna is better than 100 μm. The baseline length reaches 500 km (Fig. 8).

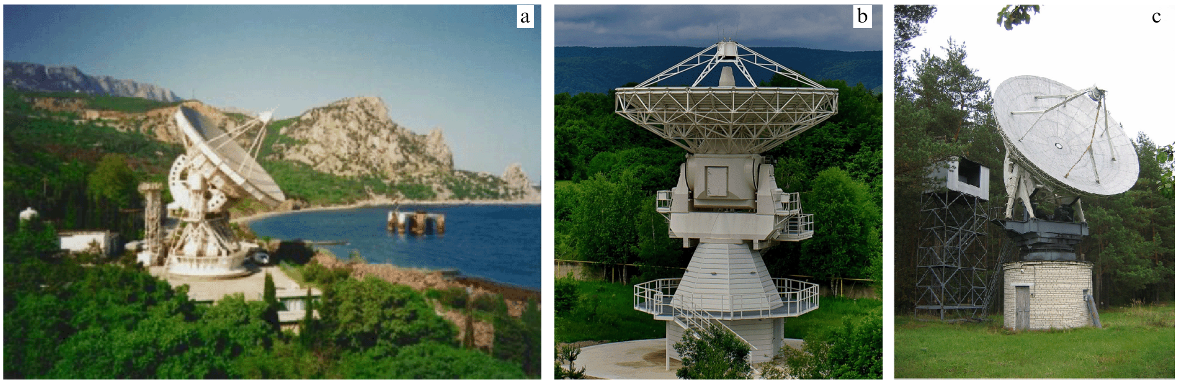

Figure 9. (a) RT-22 CrAO RAS, built in 1966. RMS surface deviation $\sim$ 0.25 mm η_A (3.4 mm) $\sim$ 20% [156]. (b) One of three RT-13 radio telescopes of the IAA RAS. RMS surface deviation $\sim$ 0.06 mm. Manufacturer VERTEX ANTENNENTECHNIK GmbH. (c) RT-7.5 of Bauman Moscow State Technical University near Moscow. RMS surface deviation $\sim$ 0.1 mm.

Unfortunately, Russian radio astronomers do not yet have millimeter and submillimeter instruments comparable in capabilities to foreign ones. The 22-meter RT-22 radio telescope of the Crimean Astrophysical Observatory (CrAO), built in the 1960s, has been used quite successfully for observations in the continuum and in spectral lines in the 3–4 mm wavelength range (Fig. 9). Surveys of a large number of molecular clouds associated with the Sharpless regions in the HCN, HCO^+ lines and their isotopologues were carried out [74–76, 152, 153]. Dark clouds were also observed [154, 155]. However, the surface accuracy of this antenna is low (RMS $\gtrsim 250$ μm). The aperture efficiency at a wavelength of 3.4 mm is $\sim$ 20% near the zenith and drops off rapidly at low angles [156].

The 7.8-meter antennas of Bauman Moscow State Technical University ($\sim$ 100 μm) and the 13-meter antennas of the Institute of Applied Astronomy of the Russian Academy of Sciences ($\sim$ 60 μm) have a better surface (Fig. 9). These antennas could be used quite effectively in the atmospheric transparency windows at wavelengths of 3 and 2 mm, but their use at shorter wavelengths is impossible due to excessive atmospheric absorption at their locations.

Therefore, the creation of a modern radio telescope (or radio telescopes) operating in the short-wavelength portion of the millimeter range and at least in the atmospheric transparency window at a wavelength of 0.85 mm is a pressing task for Russian radio astronomy. This will enable the solution of many of the above-mentioned pressing scientific problems, including participation in international projects such as the Event Horizon Telescope.

Several projects and proposals for the creation of such instruments exist, at various levels of development. Thus, the Special Astrophysical Observatory of the Russian Academy of Sciences is considering a project to create a 15-meter diameter telescope with operating wavelength ranges up to 1.3 mm [157]. As a preliminary stage, work is underway to organize observations in the millimeter wavelength range on the 6-meter optical telescope BTA. The AstroSpace Center of the Lebedev Physical Institute is working on a project to create an antenna array consisting of antennas of a relatively small diameter (3–8 m) with an operating wavelength range of up to $\sim$ 0.8 mm [139]. There is a concept of the Eurasian Submillimeter Telescope (ESMT), consisting of several antennas with a diameter of 15–20 m on the territory of the Russian Federation, China and Uzbekistan [158]. There is a proposal to build a submillimeter antenna array consisting of antennas with a diameter of 15 m in the Eastern Pamirs in Tajikistan [159]. The Vostok station in Antarctica has also been proposed as an ideal location for constructing a submillimeter telescope (S.A. Grebenev *Earth and Universe* 6 (360) 103 (2024)).

It should be noted that the tasks for single-dish antennas and antenna arrays differ somewhat. The former are more suitable for studying extended structures, while interferometers, while allowing the study of compact objects, lose information at low spatial frequencies. Data obtained from interferometers and single-dish antennas is often combined. Thus, such systems complement each other.

When selecting locations for millimeter and submillimeter antennas, the primary consideration is atmospheric absorption statistics, which in this range is determined primarily by the content of oxygen, water vapor, and liquid water in the atmosphere. Oxygen absorption is stable and, in atmospheric transparency windows, is fairly well described by an exponential dependence on altitude, with a characteristic altitude of $\sim$ 5.3 km [160]. The abundance of water in different forms varies greatly. Therefore, the suitability of a given site for millimeter and submillimeter astronomy is based on measurements and estimates of either atmospheric absorption in this range or the amount of precipitable water vapor in the atmosphere and liquid water in clouds.

A brief description of the methods and main results of such measurements and assessments is presented in the review [161]. Atmospheric absorption is estimated from atmospheric emission. This is achieved using either the so-called sky-dip method (based on relative measurements of emission intensity at different zenith angles) or absolute measurements of sky brightness temperature. Water vapor content in the atmosphere is measured using specialized radiometers operating at frequencies close to the H_2O transition frequencies (typically 22 or 183 GHz [162, 163]). Global navigation system (GNSS) signal delays are also measured for this purpose [164].

Atmospheric transparency can be estimated using an approach used to model signal propagation delays in a neutral atmosphere [165]. Publicly available data from the NASA Global Modeling and Assimilation Office model GEOS-FPIT are used[2] [159]. They estimate atmospheric parameters (specifically, air temperature, total atmospheric pressure, and partial pressure of water vapor) using a variety of ground-based, airborne, and space-based measurements,

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[2] http://gmao.gsfc.nasa.gov.

which are integrated into a dynamic model. Current models include 72 altitude levels, a spatial resolution of $0.25° \times 0.31°$, and a time resolution of 3 hours. Atmospheric absorption at any frequency can be calculated for any chosen location using standard spectroscopic parameters (e.g., [159]). Similar data are also available in the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) [166] and the European Centre for Medium-Range Weather Forecast ReAnalysis (ERA5) [167]. However, in areas with complex terrain, the spatial resolution of such models is insufficient, requiring local studies.

As a result of these studies, several sites in the Russian Federation were identified as potentially suitable for constructing a submillimeter telescope. One such site is Terskol Peak in the western Caucasus, where an optical observatory already exists. Moisture content is generally lower in the eastern Caucasus. One possible location there is Mount Kurapdag (3750 m). However, significantly better atmospheric absorption characteristics were obtained for Khulugaysha Peak in Buryatia. Conditions there are comparable to those observed in the Pamirs and Tibet. The Eastern Pamirs are similar in atmospheric absorption characteristics to the Atacama Desert [159]. Of course, Antarctica is unrivaled in terms of atmospheric transparency.

In addition to atmospheric absorption statistics, when selecting locations for new instruments, it is advisable to consider their effectiveness in global interferometric networks, primarily as part of the Event Horizon Telescope. Estimates by A.P. Lobanov (private communication) indicate that, in terms of joint observations with the Event Horizon Telescope, the optimal locations are in the Caucasus and Central Asia, up to approximately 70°E.

The development of such an instrument requires scientific and technical expertise. The Russian Federation has such expertise. Back in the 1990s, a 3 mm wavelength range SIS receiver was created at the IAP RAS in collaboration with the IRE RAS and a number of other organizations, which successfully operated on the RT-22 CrAO [153], and in the early 2000s, a dual-band (3 and 2 mm) SIS receiver was created for the 14-meter radio telescope of the Metsahovi Observatory in Finland (Fig. 10).

Currently, the IRE RAS, ASC LPI, IAP RAS, IPM RAS, and other organizations are successfully developing world-leading millimeter and submillimeter-wavelength receiving systems. These include both heterodyne (for spectral line observations) and bolometric receivers (e.g., [168–173]). As can be seen from the above, there is extensive experience conducting astrophysical research at short millimeter and submillimeter wavelengths using instruments available in Russia and around the world.

4. Conclusions

1. Millimeter and submillimeter astronomy is a vital and often unique source of information for solving a number of pressing astrophysical problems, including studies of the interstellar medium and compact objects.

2. Millimeter and submillimeter astronomy methods have yielded many important results in various fields of astrophysical research. However, a large number of pressing unsolved problems remain, stimulating further progress in this field.

3. Millimeter and submillimeter astronomy instruments are rapidly developing worldwide. Russia lags far behind in this field. There are no competitive radio telescopes in the $\lambda \lesssim 3$ mm range. At the same time, Russia has a solid foundation in conducting scientific research in this range and developing receiving equipment.

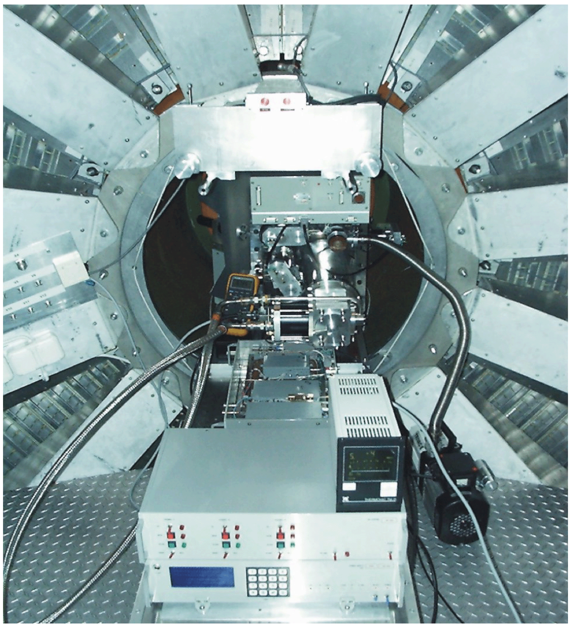

Figure 10. A dual-band (3 and 2 mm) SIS receiver, developed at the IAP RAS in collaboration with the IRE RAS and a number of other organizations, is installed on the 14-meter radio telescope of the Metsahovi Observatory in Finland (2004).

4. The creation of at least one sufficiently large telescope in this range will significantly improve the level of astrophysical research conducted in the country and allow for participation in international projects (Event Horizon Telescope).

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