Brief information about the project

Name of the project	AP13067768 Radio astronomy observations of hot cores in molecular clouds and studies of high mass star-forming regions (0122PK00201)
Relevance	One of the most important tasks of astrophysics is the study of regions and processes of star formation. Recent observational evidence gathers in favor of accretion as the preferred high-mass star formation mechanism [1]. However, it is not clear right now what is, or whether there is at all, a stellar mass limit above which disk accretion is inadequate to explain the growth of a high-mass star. Therefore, it is necessary to study the regions of star formation and associated regions of ionized hydrogen (HII) at the earliest stages of development. In this project, we carry out radio astronomical observations toward several young high-mass stars high-mass young stellar objects (HMYSOs) associated with hypercompact (HC) HII regions using a set of radio telescopes Atacama Large Millimeter Array (ALMA).
Purpose	Using our own radio observations of HMYSOs: G333.02, G337.40, G310.14AB and G345.01 at wavelengths of SO$_2$ and CH$_3$CN, construct maps of the integrated antenna temperature and velocity, study their kinematics and dynamics, to determine the extent of propagation of rotating molecular cores around embedded HC HII regions.
Objectives	1. Theoretical studies of of HMYSOs associated with HC HII regions. The implementation of this task will allow: - to carry out a review of the modern studies of the HMYSOs related to the HC HII regions located in our Galaxy; - to develop an algorithm for the study of HMYSOs. 2. Radio astronomical observations using the ALMA. The implementation of this task will allow: - to plot moment maps of rotating hot cores G333.02, G337.40, G310.14AB and G345.01 associated with the HC HII regions. - to obtain new high-resolution observational data at the wavelengths of SO$_2$ and CH$_3$CN molecules; - to improve the methodology for observing molecular clouds and hot cores; 3. Processing and analysis of the observational data. The implementation of this task will allow: - study the emission and / or absorption lines in the spectra of hot molecular cores G333.02, G337.40, G310.14AB and G345.01; - calculate the internal temperatures of hot cores G333.02, G337.40, G310.14AB and G345.01. Upon completion of the task, software codes for data processing, a methodology for analysis and comparison of the results of studies of molecular clouds and cores in the radio range will be developed.
Expected and achieved results	<u>Expected results</u> - A review of the modern studies of the HMYSOs related to the HC HII regions located in our Galaxy will be carried out; - an algorithm for the study of HMYSOs will be developed; - moment maps of rotating hot cores G333.02, G337.40, G310.14AB and G345.01 associated with the HC HII regions will be plotted; - new high-resolution observational data at the wavelengths of SO$_2$ and CH$_3$CN molecules will be obtained;

- the methodology for observing molecular clouds and hot cores will be impoved
- the emission and / or absorption lines in the spectra of hot molecular cores G333.02, G337.40, G310.14AB and G345.01 will be studied.
- the internal temperatures of hot cores G333.02, G337.40, G310.14AB and G345.01 will be calculated;
- software codes for data processing, a methodology for analysis and comparison of the results of studies of molecular clouds and nuclei in the radio range will be developed.

Achieved scientific results.

A literature review on studies of molecular clouds in the interstellar medium of Galaxy has shown that many giant molecular clouds are associated with thermal radio sources which are HII regions around young massive stars of OB class and with stellar associations. As a population of young objects which live no more than 10^8 years, giant molecular clouds concentrate toward the galactic plane. The currently accepted evolution of high-mass stars starts inside dense and massive molecular cores, where massive young stellar objects accumulate at a rate of 10^{-5} to 10^{-3} Solar masses per year. Young stars very quickly complete their Kelvin-Helmholtz (K-H) compression and reach the main sequence. At this point, the star produces large numbers of extreme ultraviolet photons, which ionize the surrounding environment. The newly formed ionized region is thought to evolve from a hypercompact HII region to a more advanced ultracompact HII region. The HC region is the first stage of development of the ionized region, characterized observationally by dimensions ≤ 0.03 pc, densities $n_e > 10^6 cm^{-3}$, emission rates $EM > 10^8$ pc/cm^6, and width of hydrogen recombination lines ≈ 50 km/s. Eventually the accretion flow will cease, and the emission of extreme ultraviolet photons and winds from the newly formed star will scatter the remaining shell material, leaving the O star surrounded by a classical HII region.

Analysis of modern research has shown that for O stars, 50% or more fraction of the final stellar mass can be expected to increase after K-H contraction and the onset of ionizing radiation. Accordingly, hypercompact HII regions are typically associated with very high column densities (NH_2 $>10^{23}$ cm^{-2}) and high frequencies (>70%) of detected falling motions toward the surrounding molecular gas. In this regard, further in the project, to better understand the collection of material from high-mass stars, the associated ionized regions will be studied at the earliest stages of their development.

The study used its own radio astronomy observations on the ALMA radio telescope complex of several hot cores associated with the region of hypercompact HII regions. The assumption of local thermodynamic equilibrium (LTE) was used to characterize the molecular gas because complex molecules form and emit in high-density molecular clouds. The rotation diagram method was used for analysis.

The hot cores observed in this project are observed by molecular emission of SO_2 and CH_3CN. These two molecules have been used before to trace the velocity gradient indicative of a rotating hot molecular core around luminous young massive stars in several cases previously described in the literature.

The main goal of the project is to determine whether rotating hot molecular nuclei are common around hypercompact regions. To achieve the goal we mapped the emission originating from two SO_2 and CH_3CN molecules in four embedded hot cores associated with HII regions using ALMA in band 6 (256.3-259.6 GHz). We observed 30(4.26)-30(3.27) and 32(4.28)-32(3.29) transitions of SO_2 and 14-13 transitions of CH_3CN. The selected SO_2 transitions have upper level temperatures of 471 and 531 K, respectively, and 14-13 transitions of CH_3CN range from 92 to 670 K.

Radio astronomical observations of hot nuclei at the wavelengths of CH_3CN and SO_2 molecules made it possible to estimate the temperatures and densities of the column of the molecular cores under study through maps of integrated antenna temperatures and determined velocities of rotating hot cores.

Hot molecular cores of **G345.0061+01.794 (**RA (J2000): 16:56:47, DEC (J2000): -40:14:25) and **G337.4032-00.4037** (RA (J2000): 16:38:50, DEC (J2000): -47:28:02) were observed in the frequency band 256.3-259.6 GHz. Radio astronomical observations on these objects were processed and calibrated, which made it possible to construct integrated antenna maps of temperature and velocity. The analysis for core G**345.0061+01.794** showed that a northeast (NE) to southwest (SW) velocity gradient with mean velocities predominantly blue shifted toward the SW direction and redshifted toward the NE source, and an emission spot with a blue shift towards the peak of the zero-order moment. The temperature of the hypercompact region near G345.01 was estimated to range from 136 K to 229 K.

The analysis of the intensity map and velocity distribution of the rotating core **G337.4032-00.4037** showed that the magnitude of the change in radiation flux is ~3-4 Jy km/s, the change in speed is from -41 km/s to -38 km/s for the 30(4.26)-30(3.27) transition of SO_2, and during the transition 32(4.28)-32(3.29) the magnitude of the change in the radiation flux is ~2-3 Jy km/s, the change in speed is from approximately -40 km /s to -37 km/s.

The analysis of the CH_3CN spectrum with a central frequency of 257.32500 GHz in the direction of the G337.4032-00.4037 core found in the continuum showed 9 components. We obtained the temperature and column density of CH_3CN for each transition. The estimated radiation area is 15". Our calculated rotation temperatures for CH_3CN (259 K) are similar to the typical hot core temperature. To obtain the rotation diagram of the observed molecule, we used LTE simulations in GILDAS. For the LTE fit, we used molecular source sizes similar to the deconvoluted size we obtained from the Gaussian fit.

The velocity distribution was obtained and a dynamic analysis was carried out for the hot cores **G345.0061+01.794** and **G337.4032-00.4037** associated with hypercompact HII regions. In order to study the physical and kinematic characteristics of the molecular environment of selected hot cores, studies were carried out on the molecular lines of high excitation CH_3CN and SO_2 and the radio recombination line H29a in the direction of hypercompact HII regions. For the core **G345.0061+01.794**, emission was detected in all observed K components of the CH_3CN molecule ($J=14\rightarrow13$) and in the SO_2 lines 30(4.26)−30(3.27) and 32(4.28)−32(3.29). The velocity-integrated molecular emission peak is located ≈0.4" northwest of the continuous emission peak. First-order moment images and channel maps illustrated a velocity gradient of 1.1 km/s/arcsec across the source, with velocities blue shifted to the west and redshift to the east, as well as the characteristic emission spot with a blueshift in the direction of the peak of the zero-order moment observed in all lines. The kinematic characteristics of the object "central blue spot" due to incident motions were simulated using the model of Estalella et al. (2019), the central mass of the core was determined to be 126.0 ± 8.7 $M_{\odot}$. From the emission in the methyl cyanide lines, using standard rotation diagram analysis, we concluded that the rotation temperature decreases from 230 K at the peak position of the molecular structure up to 137 K at its edge, indicating that our molecular observations as a hot molecular core that is in a state of internal excitation. The H29a line emission originates from a 0.65 inch region where peak coincides with the peak of the dust continuum, has a central velocity of -18.1±0.9 km/s and a width (FWHM) of 33.7±2.3 km/s. Our observations indicate that this hypercompact HII region is surrounded by a compact structure of hot molecular gas that rotates and falls towards a central mass of 126.0±8.7$M_{\odot}$, which most likely bounds the ionized region.

For **G337.4032-00.4037**, emission was detected in all observed K components of the CH_3CN molecule ($J=14\rightarrow13$) and in the SO_2 lines 30(4.26)-30(3.27) and 32(4.28)-32(3.29). The H29a Hydrogen Recombination Line was also used and all data were analyzed to compare to the continuum. In the process of analyzing the dynamics of molecular gas, motion directed from the center of the core was determined. The dynamics of molecular gas has a cometary gradient. From the orientation-velocity diagram it was found that the molecular gas has Keplerian rotation. A northeast to southwest velocity gradient was found in the thermal brightness distribution of CH_3CN. The detected velocity gradient probably reflects the outflow of matter.

The ALMA observatory's own observational data on the hot core **G310.14AB** (RA(J2000)=12:35:35, DEC(J2000)=-63:02:31) were processed and calibrated. An analysis of the temperature and radiation concentration of the gas in it was carried out. The physical and kinematic characteristics of the molecular environment of the hot core were studied by studying the molecular lines of high excitation CH_3CN and SO_2 and the radio recombination line H29a in the direction of the hypercompact HII region in it. Emission was detected in all observed K components of the CH_3CN molecule ($J=14\rightarrow13$) and in the SO_2 lines 30(4.26)-30(3.27) and 32(4.28)-32(3.29). Object G310.14AB is divided into **G310.1364-00.2249 A** (core A) and **G310.1364-00.2249 B** (core B) and is located 9 arcseconds apart. The spectra were plotted and the necessary parameters for constructing a gas distribution map were determined. From the gas distribution map, areas with a high density of columns were identified, which represent areas C1, C2. Intensity of the regions C1~(1.2 Jy/beam km/s) and C2~(1.1 Jy/beam km/s). The absorption region of the molecular gas C0 has an intensity of ~(-3 Jy/beam km/s). The maximum value of continuum radiation corresponds to the absorption zone.

The hot core **G333.0162+00.7615** has been studied. Radio astronomical observations on this object were processed and calibrated, and the temperature of the hot core and the radiation concentration of the gas in it were analyzed. Source G333.0162+00.7615 RMS was cataloged by Urquhart et al. as a candidate for a young high-mass stellar object (HMYSO). To determine whether hot molecular nuclei are common around HMYSO, we examined this source using ALMA observations at band 6 (256.3–259.6 GHz), a dust continuum, and molecular line emission originating from two molecules, SO_2 and CH_3CN (256.3–259.6 GHz). Our studies indicate that this source is not an HMYSO associated with HC HII. Instead, the gas distribution map (moment 0) reveals two compact molecular cores (A and B) that are associated with the earliest stages of a high-mass star formation region. Several features are observed in the continuum emission, two of which are associated with cores A and B, and their peak positions are located at the points (RA, DEC) (J2000) = (16:15:18.44, −49:48:44.04) and (RA, DEC) (J2000) = (16:15:17.67; 49:48:49.13) respectively. The continuum emission near the core A shows three compact sources, the brightest of which is located in the south and is not associated with molecular emission. Nine K components of this CH_3CN rotational transition were observed in this core A. An analysis of the core temperature and radiation gas concentration was carried out.

For the hot core **G333.0162+00.7615**, the dynamics of molecular gas (CH_3CN) was studied by constructing a velocity distribution map (moment 1). Velocity gradients were discovered inside two compact molecular cores (A and B): from northeast to southwest with an average speed of ~ -48 km/s in core A, as well as velocity gradients from studies of the velocity distribution map (moment 1) for SO_2 molecules (30-30) show the same features as CH_3CN, which confirms that these cores (A and B) rotate. For a hot core based on the $J=14\rightarrow13$ rotational transition of the CH_3CN molecule, the rotational temperatures of its two components - cores A and B - are calculated to be 277.6 K and 268.5 K, and the column densities are 8.01×10^{15} cm^{-2} and $4 .6\times10^{15}$ cm^{-2}, respectively.

In the hot core **G310.14AB**, integrated intensity maps (moment 0, moment 1, moment 2) and a channel map constructed for CH_3CN (v=0.14-13), SO_2 (v=0.30(4.26) molecules) -30(3.27)), SO_2 (v=0.32(4.28)-32(3.29)) provided to determine the dynamics of the molecular gas for core A. As a result, it was found that the velocity gradient for the molecular gas is directed from southeast to northwest for CH_3CN and SO_2 molecules. The direction of rotation corresponds to the position angle PA≈120°. In the gas structure of CH_3CN, the velocity gradient is determined from southeast to northwest in almost the entire volume of the structure. And in the gas structures SO_2 (v=0, 30(4.26)-30(3.27)) and SO_2 (v=0, 32(4.28)-32(3.29) the velocity gradient was determined only in the peripheral regions of molecular gas. And in areas near the center, the velocity gradient is not clearly expressed. These phenomena can be determined by comparing the maps of moment 1, moment 2 for the mentioned gases. Evidence of the existence of nuclear rotation was also observed in the channel map for CH_3CN and SO_2. The relative speed of the object is V_{rest} = -39.60 km/s. In molecular gases, the speed of which is ~ -42.4 km/s, the gas structure is located in the northwest direction. Core A with a speed of ~ -37.8 km/s is located in the southeast. That is, the location of the gas structure on both sides at values greater and less than the velocity V_{rest} proves the rotation of the core. In G310.14AB, for the region of high density of the C1 column of core A, population diagrams of the CH_3CN molecule were constructed, the density of the columns $NCH_3CN=6.716*10^{16}$ cm^{-2} and rotation temperature T_{rot}=293 K. CH_3CN was discovered on the territory of core B, but the amount of radiation is ~10 times lower than that of a comparable core A. As a result, population diagrams were constructed from core B with less intense components than from core A. As a result, the column density

	$NCH_3CN=2.853*10^{15}$ cm^{-2} and the rotation temperature T_{rot}=198.1 K were determined. The obtained results are presented and reported: 1) at International Conferences – "XXXIst International Astronomical Union General Assembly (IAUGA-2022)" in Busan (Republic of Korea), 2022; – “Wheel of Star Formation — A conference dedicated to Prof. Jan Palouš” (Prague, Czech Republic), 2022; – “Protostars and Planets VII” (Kyoto, Japan), 2023; – “Cosmic Masers: Proper Motion towards the Next-Generation Large Projects” (Kagoshima, Japan), 2023; – “Farabi Alemi” (Almaty, Kazakhstan), 2022-2023; – “Abdildin okulary: Zamanaui fizikanyn kokeikesti maseleleri” (Almaty, Kazakhstan), 2023. 2) at scientific seminars of summer schools – “Central Asia radio-Astronomy Training Workshop” (Urumqi, China, August 15-26, 2023) – “IAU I-HOW Radio Astronomy Workshop” (Kayseri, Turkey, September 4-15, 2023)
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Patents	-