ABSTRACT

dissertation for the degree of Doctor of Philosophy (PhD) in specialty - 8D05307 “Physics and Astronomy”

OMAR ARUZHAN ZHENISKHANKIZI

Thesis topic: “Molecular line observations of star-forming regions in the interstellar cloud”

General description of work. One of the most important tasks of astrophysics is the study of areas and processes of star formation. The results of observations of star-forming regions in recent years increasingly provide evidence in favor of the accretion mechanism for the formation of massive stars. However, the question of the existence of a stellar mass limit remains unclear, above which the disk accretion mechanism is insufficient to explain the growth of a high-mass star. It is therefore necessary to study star forming regions and associated hydrogen ionized (HII) regions at the earliest stages of development. We propose to use the high angular resolution Atacama Large Millimeter Array (ALMA) Band 6 to test a key prediction of this hypothesis, which is that all HC HII regions should be associated with a rotating hot molecular core. To do this, we target young high-mass stars associated with hypercompact HII regions: G345.0061+01.7944B, G333.0162+00.7615 and G337.4032-00.4037, looking for velocity gradients corresponding to a rotating core at scales of 3000 AU. using the high energy transitions SO_2 304.26-303.27, 324.28-323.29 and CH_3CN 14-13. We also observe emission from the ionized gas, traced along the H29α recombination line. The general presence of orbiting core around hypercompact HII regions will help us confirm the hypotheses of this simple model.

Relevance of the topic. Stars are born in star-shaped molecular clouds, and studying the early stages of the formation of stellar regions is of great importance for both astronomy and cosmology. It helps to understand the evolutionary cycle of stars and understand the structure and dynamics of galaxies as a whole. Using radio telescopes, it is possible to study the radiation of many molecules, such as carbon monoxide CO, hydrogen cyanide HCN and others, coming from star forming regions. In the star-shaped regions of young stars, powerful ejections of matter called protostellar accretion jets are detected, which are studied through the radio emission of water molecules H_2O or methanol CH_3OH. These ejections can provide information about stellar mass dynamics, including the loss of angular momentum of the star. Studies of methyl cyanide CH_3CN and sulfur dioxide SO_2 in star-shaped regions are important for astrochemistry and reveal the main molecules that contribute to chemical evolution in star-shaped regions where pure molecular clouds form, representing the birthplaces of stars. Gas density, temperature characteristics, kinematics and chemical composition of gas in star forming regions can be determined through the study of radiation. Radio astronomy observations help to understand the structure and physics of disks and shells around young stars, and also help in studying the evolution of objects of their accompanying objects associated

with the phases of their evolution, and can also map gas conditions in galaxies to understand the processes of star formation.

Purpose of the dissertation - To study the molecular gas composition of hot core in the HII regions of galactic clouds in order to characterize their kinematics and dynamics, integral maps of the intensity and velocity of methyl cyanide (CH_3CN) and sulfur dioxide (SO_2) are created. These maps provide insight into the characteristics and dynamics of gases in different parts of space through velocity gradients. Observations of H29α radio recombination lines are used to directly measure ionized gas, allowing the evolution and physical parameters of star-forming HII regions to be determined.

Research objectives.

1. First-order processing and calibration of observational data from the high-frequency complex of the ALMA high-angular resolution radio telescope for studying hot core at wavelengths CH_3CN and SO_2;
2. Determination of the types of molecular lines from spectral observation windows for each nucleus based on astrospectroscopic catalogs CDMS, JPL, using the Splatologue database, study of emission lines;
3. Construction of integrated maps of the intensity and velocity of molecular core G345.0061+01.7944B, G333.0162+00.7615 and G337.4032-00.4037;
4. Determination of the physical parameters of the molecular core G345.0061+01.7944B, G333.0162+00.7615 and G337.4032-00.4037 by the rotation diagram method;
5. Determination of the physical parameters of the hypercompact HII regions around the hot molecular core G345.0061+01.7944B and G337.4032-00.4037 based on an analysis of observations of the H29α radio recombination line.

Objects of research: Study of the molecular core G345.0061+01.7944B, G337.4032-00.4037 and binuclear G333.0162+00.7615 associated with regions of ionized hydrogen HII.

Research methods. The dissertation research used methods for studying continuum observations of radio astronomical molecular lines and hydrogen recombination lines. Data processing and calibration of these observations were performed using Common Astronomy and Software Applications (CASA), and the continuum was subtracted with a selection of visible free channels using CASA uvcontsub to obtain a clean continuum image in the tclean application. Gildas (Class), MAdrid Data Cube Analysis (MADCUBA), CARTA, and programs for processing unique radio astronomy studies were used to carry out the main processing. The construction and visualization of the final results were obtained in the Python programming language. The Splatalogue, JPL, and CDMS catalogs were used as spectroscopic databases.

Basic provisions submitted for defense. The following provisions are submitted for defense:

1. The H29α radio recombination line is detected in the hot molecular nucleus G345.0061+01.794B and corresponds to the HII region with physical parameters: T_e=8094 ± 1534 K, n_e=(2.1 ± 0.2)× 105 cm−3, (3.6 ± 0.3)×10−3

$M_\odot$, which classifies it as a hypercompact type with a massive star equivalent to the zero-age main sequence of type O5.5.

2. Analysis of the observation of molecular emission lines of CH_3CN and SO_2 observed in the direction of the hypercompact HII region of the hot core G345.0061+01.794B revealed falling movements of molecular gas towards the central part of a massive star with a mass of 172.8±8.8 $M_\odot$
3. Observations of dust continuum, molecular emission and radio recombination emission revealed two new hot core in the region G333.0162+00.7615, belonging to the earliest stage of the high mass star forming region with a temperature of about 300 K.

Scientific novelty of the work:

1. Observational data from the high-angular-resolution high-frequency radio telescope complex ALMA was used to study hot core at the wavelengths of CH_3CN and SO_2.
2. Based on the observational spectral windows for each nucleus, the types of molecular lines were determined based on the astrospectroscopic catalogs CDMS, JPL, using the Splatologue database and the emission lines were studied.
3. Integrated maps of the intensity and velocity of molecular core G345.0061+01.7944B, G333.0162+00.7615 and G337.4032-00.4037 were constructed.
4. The physical parameters of the molecular core G345.0061+01.7944B, G333.0162+00.7615 and G337.4032-00.4037 were determined by the rotation diagram method.
5. By analyzing observations of the H29α radio recombination line, the physical parameters of the hypercompact HII regions around the hot molecular core of the hot molecular core G345.0061+01.7944B and G337.4032-00.4037 were determined.
6. An algorithm and methods for studying the formation and stages of young high-mass stellar objects have been created.
7. When processing data, unique radio astronomy programs were used and program codes were created.

Theoretical and practical significance of the work. The results obtained from radio observations of star formation regions in molecular clouds can find practical application in various aspects of astronomy and astrophysics, as well as in applied problems:

Development of theoretical models; The results can improve existing theoretical models of star formation and contribute to the development of new concepts. This could lead to a deeper understanding of star formation processes and improve the accuracy of predicting the evolution of molecular clouds.

Organization of observation programs: The results of the work can serve as the basis for organizing observation programs aimed at studying the formation of stars in molecular clouds. This helps optimize the use of astronomical resources and increase the efficiency of observations.

Improving the efficiency and accuracy of research: Practical applications of

research results can improve the efficiency and accuracy of astronomical studies of star formation and molecular cloud evolution. This may include improving data analysis methods, optimizing monitoring strategies, and developing new tools and techniques.

Potential for technological development: The results of the work may also contribute to the development of technologies and methods of astronomical observations. This may include developing new tools and technologies, improving existing tools and data processing methods.

Thus, the work not only expands our theoretical understanding of star formation, but also has practical potential for improving methods and tools for astronomical research, as well as for applications in astronomy and astrophysics.

Personal contribution of the author.

The author of the dissertation analyzed the literature on star formation regions and processed data from high-frequency observations of ALMA Band 6. During the processing, unique applied radio astronomy programs Gildas, CASA, Madcuba, Carta, DS9 were mastered, as a result of which the final description and mapping and calculations of the physical parameters of the HII regions were carried out on Python programming language. The objectives and conclusions of the study were agreed upon jointly with the scientific supervisors.

Reliability of results. The reliability of the scientific conclusions of the work is confirmed by their compliance with theoretical models and conclusions about the nature of similar objects obtained by other authors.

Approbation of work. The results of the dissertation were presented and discussed. Based on the materials of the dissertation work, 7 publications were published:

An article with a high impact factor in publications included in the Thomson Reuters database or the international scientific database Scopus:

1. Komesh T., Garay G., Henkel C., **Omar A**., Estalella R., Assembay Z., Li D., et al., Infall Motions in the Hot Core Associated with Hypercompact HII Region G345.0061+01.794 B //The Astrophysical Journal. - 2024.-V.967.-№.1.-P.15.DOI: 10.3847/1538-4357/ad3e7b [Q1]
2. Komesh T., **Omar A.,** Garay G., Assembay Z., Alimgazinova N., Zhumabay N., Kyzgarina, M. ALMA observations of the environments of G333. 0162+ 00.7615 //IAU Symposium. – 2023. – V. 373. – P. 35-38 [Q4].
3. Assembay Z., Komesh T., Garay G., **Omar A.,** Esimbek J., Alimgazinova N. ALMA observations of the environments of G301. 1364-00.2249 A //IAU Symposium. – 2024. – V. 380. – P. 204-206 [Q4].

Articles in publications recommended by the Scientific Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan:

1. **Omar A.Z.,** Manapbayeva A. B., Komesh T., Kyzgarina M.T., Alimgazinova N.Sh., Studies of regions in the Aquila molecular cloud by the method of CO selective dissociation // Reports of the National academy of sciences of the Republic of Kazakhstan – 2023. - V. 345(1), - P. 180–191.

   2. Manapbayeva A. B., **Omar A.Zh.**, Alimgazinova N.Sh., Komesh T., Kyzgarina M.T., Esimbek J., Assembay Zh.. Determination of physical

parameters of the W40 HII region using observations of H110 radio recombination line // Recent Contributions to Physics, 2023. - №3– P.4-11

Publications in the collection of dissertations:

1. **Omar A.Zh.,** Mukhan A., Rotating hot cores confined to hypercompact HII regions//Proceedings of the international scientific conference of students and young scientists “FARABI ALEMI”. - Almaty. – 2021. – P.213.
2. **Omar A.Zh.,** Molecular line observations of a rotating hot core confined to the hypercompact HII region//Proceedings of the international scientific conference of students and young scientists “FARABI ALEMI”. - Almaty. – 2022.– P.210.

The results of the dissertation were discussed at scientific seminars with foreign scientists:

Professors of the Xinjiang Astronomical Observatory, Urumqi, China in 2023: **Esimbek Jarken, Christian Henkel;**

“The IAU/IHOW Radio Astronomy 2023”, held in Kayseri, Turkey in 2023, **George Bendo, Aida Ahmadi;**

October 10, 2023 Professor **Guido Garay** from the University of Chile (on the ZOOM platform);

In 2024, Nazarbayev University, Energy Space Laboratory of the Ural Federal University, **Professor A.M. Sobolev;**

Connection of the dissertation topic with plans for scientific work

The dissertation work was carried out in accordance with the plan of fundamental research works of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan “Grant funding for scientific research” on the topic “AR13067768 - Radio astronomical study of hot core in molecular clouds and the study of star formation regions of massive stars.”

Structure and scope of the dissertation.

The dissertation consists of an introduction, 4 parts, a conclusion, and a list of references. The work consists of 118 pages, including 107 pages of printed text, 83 drawings, 17 formulas, 10 tables and a bibliography with 110 titles.