Short summary of PhD thesis

Earliest phases of star formation

Multispectral view of the structures of the very cold interstellar medium and the associated star formation

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Introduction

One of the most active research areas in astrophysics is the investigation of the earliest phases of star formation and the physical parameters of young stellar objects. The study of this research area started decades ago in several institutes in Hungary, such as the Konkoly Observatory, the Eötvös University, the University of Szeged and the Gothard Astrophysical Observatory and it is still on-going at a high level with international collaborations.

The cold, dense interstellar matter, where star formation occurs, is mainly observable at infrared and submillimeter wavelengths. The all-sky survey of the Planck satellite gave us the possibility to reveal the cold clumps in the whole Galaxy. The international Galactic Cold Cores collaboration identified the sources and made the catalog of these objects. In 2009 the Astronomy Department of the Eötvös University joined this collaboration. My PhD research was performed as part of this international team under the supervision of L. Viktor Toth, the leading researcher at the Eötvös University on this project. Our group's main aims were the investigation of the Galactic distribution and physical properties of the Planck cold clumps, and the multispectral study of selected objects based on the Herschel Space Observatory and follow-up observations.

Objectives

Nearby, isolated molecular clouds are traditionally the targets of early star formation studies. The acquired knowledge gives us information about these selected regions. Thanks to the Planck all-sky survey, the identification of the cold clumps in the whole Galaxy was possible and with high-resolution follow up measurements, we can characterize their properties. How are they distributed in the Galaxy? Is there any structure in their distribution? Are the physical parameters of the cold clumps the same in the different parts of the Galaxy?

We can also identify the sources with extreme mass or column density values, and also the sources lying at unusual parts of the Galaxy, e.g. without active star formation. Do all cold clumps form stars?

My aim was to find answers to these questions. The objectives of my research were the following:

- Study of medium scale (50-100 pc) distribution of Planck cold clumps in the Galaxy. Identification and characterization of groups with modern mathematical methods.

- Investigation of the structure of Planck cold clumps using my own observations as well as observations from our international team: infrared photometry from Herschel and radio spectroscopic data (NH_3, N_2H^+).

- Identification and characterization of cold, dense cloud cores with radiative transfer simulation.

- Characterization of star formation properties of Planck cold clumps. Identification of young stellar objects and estimation of stellar parameters based on multispectral photometric data and pre-computed young stellar object models.

- Study of the star formation in space and time taking into account the environmental parameters.

Applied methods

I investigated the medium-scale clustering of Planck cold clumps with the minimum spanning tree method and compared the results with Monte Carlo simulated samples.

I collected photometric data from archive databases to characterize the properties of young stellar objects. I estimated the parameters of the star-disc-envelope system by selecting the best fitting models from an online database.

In case of the Planck clump G163.82-8.44 I used the CPPSIMU software to model the observed ammonia line intensities. I used Python scripts to prepare the three dimensional distribution of the density and temperature of the object.

I used Python and IDL scripts for analyzing, processing and plotting the data. For the preparation of the radio spectroscopic observations and reduction and analysis of the observed data, I used the appropriate softwares (ASTRO, CLASS, GREG) from the Gildas software package.

Theses

1. I studied the distribution of Planck cold clumps for the whole sky and in the well-known, nearby complex of the Taurus-Auriga-Perseus and California star-forming clouds. I identified clump pairs and groups in the Planck cloud sample (C3PO) and compared my results with Monte Carlo simulated (MC) samples. For the all-sky data, the MC samples show 30% fewer groups (at 25-σ) than in C3PO. The fraction of larger groups (with at least 4 members) is 38% in the Taurus-Orion region and 28% over the whole sky. These fractions are significantly higher than the mean values derived from the MC simulations. However, the mean elongation of the filaments in the MC samples does not differ from that in C3PO.

2. I derived the parameters (distance, size, dust temperature, column density and mass) of 48 Planck cloud clumps covered by the Herschel Hi-GAL survey in the Galactic Plane. Most of the Planck clumps contain signs of star formation. About 25% of the clumps are massive enough to form high-mass stars and star clusters since they exceed the empirical threshold for massive star formation. Planck clumps toward the Galactic center region show higher peak column densities and higher average dust temperatures than those of the clumps in the outer Galaxy. I identified five particularly interesting objects in the Galactic plane that are good candidates for higher resolution continuum and molecular line studies. Three of these objects, located in the inner Galaxy, fulfill the criteria of massive star and star cluster formation, and do not show evidence of high mass star formation. These objects are thus excellent templates to study the earliest phases of massive star and star cluster formation. Two objects were found in the outer part of the Galaxy, which also fulfill the massive star formation criteria and already show signs of massive star formation.

3. High Galactic latitude clouds with $|b|>30$ are usually nearby, low density clouds without signs of star formation. Based on previous studies, there are two clouds, L1642 and MBM12, which show active star formation. I studied the infrared sources in the direction of L1642 and estimated the parameters of three young stellar objects. Their masses are between 0,2-1,6 $M_\odot$, and temperatures are 2800-4600 K. One of the sources appears to be a young stellar

object forming inside the L1642 cloud, instead of a foreground brown dwarf, as previously classified.

4. In the California nebulae I have characterized the star formation, which started several million years ago and the formation of low- and medium-mass stars is still on-going. I analyzed 62 infrared point sources in the G163.82-8.44 Planck cold clump and found 11 low-mass and 2 medium-mass young stellar objects at different evolutionary stages. I estimated their parameters with the use of pre-computed YSO models. Their estimated masses are between 0,1-5,5 $M_{\odot}$, with temperatures of 3500-7500 K.

5. In the California nebulae, I identified the densest core in the G163.82-8.44 Planck cold clump based on Herschel data and observed this core with the Effelsberg 100 m telescope. I have found a core with double velocity components based on observations of the ammonia spectral line. The good signal-to-noise ratio of the data, coupled with high velocity-resolution, allowed me to model the density and temperature profile of the core with radiative transfer modeling. The temperature of the cores are the same, however their sizes and masses differ with factors of 6 and 10, respectively.

6. Previous Herschel observations of the infrared dark cloud, G11.09-0.10 revealed more than 20 cores in different evolutionary stages. I selected a subregion with three cores in different evolutionary stages and investigated them with molecular line observation from the PdBI interferometer. In three cores of the G11.09-0.10 Planck cold clump, I identified 9 fragments with interferometric observations. Their sizes are 0.08-0.17 pc and their masses are 6-45 $M_{\odot}$. Two of the cores are gravitationally bound.

Conclusion and outlook

Based on the MST method, strong clustering was seen for the Planck cold clumps. The distribution of cold, dense interstellar matter shows structures as large as typical, isolated molecular clouds. The cold clumps located close to the Galactic Center show higher temperature and density values than the average.

I studied the star formation at low-, medium- and high- galactic latitudes. All regions show star-formation, but not every Planck cold clump has associated young stellar sources. In larger clump clusters, stars can form continuously for several million years.

The next steps towards the detailed study of the interstellar matter are large radio spectroscopic surveys to evaluate the molecular content of Planck cold clumps. We performed an extensive study for the Taurus-Auriga-Perseues and California star-forming regions with the 1.85 m telescope in Osaka. Our results will be published later this year.

The Planck cold clumps show a broad variety of physical parameters and star-forming properties. They are at the focus of attention of different international research groups. Several thousands of cold clumps are surveyed as part of three main projects: TOP (TRAO Observations of Planck cold clumps), SCOPE (SCUBA-2 Continuum Observations of Pre-protostellar Evolution[1]) and SAMPLING (SMT "All-sky" Mapping of PLanck Interstellar Nebulae in the Galaxy[2]). SAMPLING is one of the ESO Public Surveys, where we will obtain ^{12}CO and ^{13}CO (2-1) maps toward ~600 Planck clumps, using the SMT 12m telescope of the Arizona Radio Observatory.

We study 11 high-mass star-forming dense cores from the Hi-GAL region in different evolutionary stages with the APEX 12 m telescope. This is a joint project between ELTE, ESO, MPE, Arcetri Astrophysical Observatory and Queen Mary University of London. Our aim is to study the chemical evolution of the cores based on molecular abundances and fractionation. The observed deuteration fraction decreases with the evolutionary stage – this first results will be published in autumn 2016.

As I have shown for the Planck clump G163.82-8.44 and for the California nebulae in my thesis, we can successfully estimate the physical parameters of star-disc-envelope systems and characterize the star formation properties of the cold clumps using multispectral datasets. As part of a collaboration with the University of Arizona, we are characterizing the star formation in several other star-forming regions.

[1]https://www.eaobservatory.org/jcmt/science/large-programs/scope/
[2]http://sky-sampling.github.io/

Papers related to the theses

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