SHORT SUMMARY OF PhD THESIS

Star formation on the galactic interfaces

Analysis of the large scale distribution of the Milky Way's pre- and proto-stellar objects on the dense-diffuse interfaces of the interstellar matter

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Introduction

The lifetime of high mass stars is relatively short ($\sim 3 \times 10^6$ in case of 10 solar masses), therefore star formation did not start at one time and does not end at the same time, it is an ongoing process. The position and evolution of stars impacts the small- and large-scale distribution, chemical evolution of interstellar medium (ISM), but they have impact on the planet formation in their vicinity, as well. The young stellar objects (YSOs) are formed from the ISM, thus the ISM distribution determines the location of YSOs.

In my thesis ISM means the dust, and atomic and molecular gas found between the stars, which has a density ranging from $\sim$100cm^{-3} to $\sim$10^{6}cm^{-3} and temperature between 10 and 10^{7}K. It has a hierarchical structure, where the hot, diffuse ISM and the cold, dense ISM are in equilibrium. In the ISM distribution of nearby galaxies, and in our own galaxy as well, shells, arcs, bubbles and rings are observed due to the radio emission of the excited atoms and molecules and through the thermal emission of the dust that are building up these structures. These structures are mainly formed by the the stellar wind of high mass OB stars and by supernova explosions. The energy released in these processes forms a shock wave. In front of the shock wave the ISM is swept up and a denser shell is created. This means that the ISM density is low in the vicinity of the central source, the number of particles is $\sim 10^4$cm^{-3}. With increasing radial distance one reaches the swept up material where the density has a strong gradient. The density in these regions can be 10 or even 100 times higher. So the formed bubbles, shells, rings are interfaces between the low- and high-density ISM. In these regions gravitational instabilities may occur, leading to fragmentation, formation of new cloud cores and YSOs.

The first step leading to the formation of YSOs is the contraction of the cloud cores. This is initially isotherm, because the collapsing medium is opaque for the thermal radiation. After reaching a critical density, the infrared radiation cannot leave the core, the temperature and pressure increases. The dust located in the core has a temperature of around 10 K, so the thermal radiation peaks at sub-mm wavelengths. Because of the increasing temperature the molecules (mainly hydrogen) start to dissociate. Therefore the equilibrium disappears, the core rapidly collapses and the protostar forms.

Protostars are born $\sim$10 thousand years after the collapse of the core stars. At this stage the star and the protoplanetary disk are deeply embedded in a common envelope. With the evolution of the embedded star the temperature keeps rising. This shifts the spectral energy distribution's peak to the far-infrared regime. The accretaion from the disk matter causes bi-polar outflows. As a consequence the medium which leaves from the direction of the poles also takes material from the envelope. This process is observable 10^5 years after the beginning of the collapse. The stellar winds then blow away all the material apart from the disk, and the disk becomes passive. Its main energy source is not the accretion any more, but the radiation from the central star. This state is observable after about 1 million years. In the end the gas and dust which built up the disk, dissipates, or larger bodies are formed with coagulation. Because of the warming of the more diffuse dust envelope and of the proto-planetary disk, the pre-main sequence young stars become observable at mid- and near-infrared wavelengths.

Objectives

There are many open questions regarding the processes that initiate the star formation and how these processes occur. The correlation between the ISM distribution, the star formation and the position of the young stars has been studied only on isolated regions of the sky. It is not known if the location of the cold cloud cores is connected to the location of the interfaces between the high and low density ISM. What does the YSOs galactic distribution look like? Is it possible to create such a catalog that helps us to study it? We have knowledge of expanding bubbles which likely played a role in the star formation scenario of a given region. But how general is this phenomenon? Is there a statistical correlation between star formation and the interfaces of the high and low density ISM?

My dissertation aims to give more accurate answers than we had before. The following objectives led to the answers:

- The distribution of cloud clumps being in the first stages of star formation needed to be analysed, and the correlation with the bubbles, shells and loops needed to be studied along with the strength of the correlation.

- In order to study the connection of the YSOs and the interfaces, a YSO catalogue needed to be prepared with numerous objects and with suitably small number of contaminant objects (mainly infrared luminous evolved stars and extragalaxies). Such modern statistical method needed to be found and applied which gives more reliable results than the generally used methods.

- The YSO surface density distribution needed to be compared to the distribution of the interfaces. The uncertainty of the result had to be tested.

- To separate the signal of compact sources and that of the diffuse background emission in the state-of-the-art Herschel Observatory measurements, a new method needed to be developed. Instead of working on the projected maps, the algorithm had to solve the problem in the timeline measurements. The reliability of the method needed to be tested.

Applied methods

- I investigated the correlation between the interfaces, the extended and pointsources based on their celestial position and their surface density relative to the interstellar reddening. I determined the correlation's significance with statistical methods based on Monte-Carlo simulations.

- I classified the AKARI and WISE sources with Quadratic Discriminant Analysis. I created the teaching samples with positional correlation based on the SIMBAD database. The goodness of the classification and the contamination was estimated with the help of objects from known object types also based on the SIMABD, by counting the false-positive and positive classifications. The results were compared to that of generally accepted and widely used methods.

- The clusters of YSOs in the LDN 1188 dark cloud were defined with the Minimum Spanning Tree method. The relation of the CO cores and the YSOs was analysed based on their celestial position.

- To separate the signal of the sources and the diffuse background emission in the Herschel Observatory's timeline I used the boloSource algorithm which was partially developed and fully tested by me. The goodness of the photometric results were studied with statistical methods based on the photospheric models of faint standard stars.

- I wrote the data processing and plotting scripts in the IDL (Interactive Data Language) programming language. I used the Jython programming language of the Herschel Interactive Processing Environment (HIPE) to develop and test the boloSource algorithm and to process the Herschel data. I used R software and scripting language to solve problems related to discriminant analysis and statistics.

Theses

1. The distribution of dense, cold interstellar cloud cores detected by Planck (C3PO) correlates well with that of the high and low density interfaces being located in the ISM. Significant excess is observable in the direction of the HI shells and infrared loops. The excess is more significant on the infrared loops. Based on a one sample t test the value of the significance is 748. The observed excess is not due to the higher ISM column density. The significance of the surface density excess relative to the interstellar reddening is 737, based on a one sample t test.

2. I classified the AKARI far-infrared point sources into three classes: galaxy, evolved star and YSO. I compared the results of generally accepted and widely used methods based on colour-colour and colour-magnitude diagrams to the results of the linear and quadratic discriminant analysis (LDA and QDA). With additional mid-infrared WISE data I was able to compile a YSO catalogue of 44001 sources, based on the QDA. Based on the previously known objects I found that the classification's goodness is 93% while the contamination is only 5%.

3. I analysed the surface density distribution of the AKARI YSOs and compared it to that of the infrared loops. Based on a one sample t test I found that the significancy of the excess found on the loops is 648. I gave a detailed descrition of those loops which were found more active than the others. 93% of the actively star forming loops are located in the outer Galaxy, therefore separated analysis was carried out for this region. 48% of the YSOs located here, are formed in the direction of the loops, the value of the significance is 865. The physical properties of the numerous cold cloud cores observed by the Herschel Observatory's Cold Cores program were analysed. Those cores apparently associated with YSOs have $\sim 3\times$ higher density and $\sim 2-10\times$ higher mass than those without YSOs.

4. Based on WISE mid-infrared and additional 2MASS near-infrared data I created a catalogue of $\sim 2.5 million$ YSOs. I compared the reults to a previously published

methon and I found that my catalog contains YSOs with higher reliability and with lower contamination. With the help of the catalogue I studied the star formation in the LDN 1188 dark cloud located in the Cepheus bubble. I found that at the same time cloud cores and YSOs with different evolutionary stages are located in the region.

5. I participated in the development of the boloSource algorithm and performed the optimisation. I removed the signal of compact sources from the Herschel Observatory's observational timeline instead of removing them from the position-position space of the projected maps. This way I was able to preserve the noise spectra of the measurement. I created maps from the source-only timeline data and I compared the sorces' measured flux to the results of the usual aperture photometry. The difference between the results of the different methods was found to be less than the 3-5% photometric error. The contamination caused by the background galaxies and diffuse emission is more problematic in the $160\mu m$ observations, where I found that the new method increases the photometric accuracy with $\sim 50\%$.

Conclusion

The interfaces between the high and low density ISM are special places of star formation, because the dense, cold cloud cores and the YSOs show number and surface density excess here compared to that predicted by simulations. In the outer Galaxy, on moderate galactic latitudes, the $\sim$48% of YSOs are located on these interfaces defined by the infrared loops. Significant percentage of the star formation takes place in regions where some external forces affected the molecular clouds. This is in good agreement with the theories claiming that in bubbles and loops the medium is swept up to layers where gravitational instabilities lead to cloud clump and core formation in which new stars might born in higher rate than it is observable in other regions. In the studied regions star formation on the interfaces is a general phenomena, the expanding loops and shells can help the formation of new stars.

With the help of the Quadratic Discriminant Analysis one is able to classify not only YSOs. With the appropriate teaching sample we are able to compile more accurate galaxy catalogues which may play an important role in the analysis of the large scale structures of the Universe. Besides the galaxies there are plenty of objects, that are located in our Galaxy and for their classification QDA can be a useful tool.

The compiled YSO catalogues can be used for further research. One example is the Spitzer Coreshine project, which is the largest approved "Cycle 8" Warm Spitzer mission in the Galactic science category, and it uses the AKARI catalogue. The WISE YSO catalogue is also useful for other studies. In my dissertation I shortly mentioned the triggered star formation in the Rosette molecular cloud. Another application is the studies of star formation outside the galactic plane. The successful ESO HAWK-I proposal targeted the detailed star formation of the clump G343.89-2.40 detected by Planck and it relied on the WISE YSOs. Further important application could be that with such an all-sky selection more accurate Milky Way models can be created.

The boloSource algorithm is currently used in various Herschel projects. One of them is the Cold Cores project studying the circumstances of star formation in the vicinity of the dense cold cloud cores. The source-free maps help to create column density and

temperature maps. Another application of the algorithm is the infrared variability study in the IC348 star forming region. The code is useful to determine the far-infrared light curve of the variable sources. The algorithm plays an important role in the "TNO's Are Cool!" Key Project, where the determination of the light curve of small solar system bodies is critical. In general this is difficult because of the numerous luminous background galaxies, but with the boloSource they can be eliminated.

References

Papers related to the theses

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5. Tóth, L. V.; **Marton, G.**; Zahorecz, S.; Balázs, L. G.; Ueno, M.; Tamura, M.; Kawamura, A.; Kiss, Z. T.; Kitamura, Y., *The AKARI FIS YSO Catalogue*, 2013, Publication of the Astronomical Society of Japan, közlésre elfogadva

6. **Marton, G.**; Verebélyi, E.; Kiss, Cs.; Smidla, J., *Newly identified YSO candidates towards the LDN 1188*, 2013, Astronomische Nachrichten, közlésre elfogadva

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Other publications related to the theses

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3. **Marton, G.**; Kiss, Z. T.; Tóth, L. V.; Zahorecz, S.; Pásztor, L.; Ueno, M.; Kitamura, Y.; Tamura, M.; Kawamura, A.; Onishi, T., *YSO Clusters on Galactic Infrared Loops*, 2012, Star Clusters in the Era of Large Surveys, Astrophysics and Space Science Proceedings, ISBN 978-3-642-22112-5

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Talks and posters

2009

- Young European Radio Astronomers Conference, Porto, Portugal - talk

2010

- Workshop of Young Researchers in Astronomy and Astrophysics, Budapest, Hungary - talk
- Joint European and National Astronomy Meeting, Lisbon, Portugal - poster
- Cold Cores meeting, Budapest, Hungary - talk

2011

- The millimeter and submillimeter sky in the planck mission era - Planck Conference, Paris, France - talk
- The Milky Way in the Herschel Era, Rome, Italy - poster
- Cold Cores meeting, Helsinki, Finland - talk
- Herschel PACS ICC meeting, Garching, Germany - talk

2012

- Cold Cores meeting, Budapest, Hungary - talk
- Herschel PACS ICC meeting, Madrid, Spain - talk

- Workshop of Young Researchers in Astronomy and Astrophysics, Budapest, Hungary - talk
- IAU GA Special Session 15 (Data intensive astronomy), Beijing, China - talk

2013

- Herschel Mapmaking Workshop, Madrid, Spain - talk
- Herschel Calibration Workshop, Madrid, Spain - poster
- Protostars & Planets VI, Heidelberg, Germany - poster