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Review of the doctoral thesis of
Ngan Thi My Le
Uniwersytet Mikołaja Kopernika
Wydział Fizyki, Astronomii i Informatyki Stosowanej
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entitled:
Multi-wavelength observations of the outer Galaxy: Identifying the impact of environment on star formation
supervisors:
Prof. dr hab Michał Hanasz
Dr Agata Karska

The thesis of Ngan Le tackles the topic of star formation in the Galaxy and how it is impacted by the parameters of the environment. In particular, the role of the magnetic fields and metallicity is investigated by a very detailed characterisation of the parameters of the molecular clouds in different regions of the Galaxy. The subject is very timely due to the significant recent advancements in far-infrared instrumentation, which are greatly enhancing our capacity for comprehensive investigations into the obscure regions of star formation. The Author uses a very broad range of data types in the thesis. Many of these data were acquired through the active participation of the student, her research collaborators or supervisors. However, the Author's ability to process observational data to make it scientifically useful is a notable skill gained during the doctoral studies and shown in this thesis. In particular, the data from complex infrared and radio facilities were used, for example, infrared spectra from NASA IRTF and VLT/KMOS, data from space or near-space observatories such as Herschel or SOFIA and radio data from Torun's own RT4 radiotelescope.

The work comprises 138 pages and contains six chapters, including the introduction, and description of methods, followed by research chapters published or soon-to-be-submitted to high-profile astrophysical journals and the final chapter with a summary. The presentation and layout of the thesis are very good, with numerous figures and tables. The English in the text is of excellent quality and easy to read. I found only a small number of typos (in particular in Chapter 3) and minor typing errors as well I too small axes labels in some figures, e.g. Fig. 4.C.1. This, however, does not diminish the overall positive reception of the thesis.

Chapters 1 and 2 are the introduction to the thesis, providing an overview of the physics behind stellar formation from molecular clouds, with particular emphasis on low-mass stars. Additionally, these chapters delve into the characterization of Young Stellar Objects (YSOs) and their various classes. This is followed by the description of the star-forming regions of interest, i.e. Oph-A and CMa-l224, and the instruments used. In the brief Chapter 2, the Author introduces the methodology of the applied astrophysical analysis, although it appears that this introduction is primarily relevant to Chapter 3. Remaining research Chapters 4 and 5 independently provide detailed descriptions of their own methodologies, which should have been briefly incorporated into Chapter 2.

Chapter 3 tackles studies of Ophiuchus A cloud and is planned to be submitted to the Astronomy and Astrophysics Journal. The main focus of the work is on polarimetric studies at far-infrared bands in order to investigate the morphology of the magnetic fields. The data used in this work were collected using SOFIA's far-infrared polarimeter (HAWC+) and were obtained from the SOFIA's archive. Data for spectroscopy of molecular lines came from 15-m JCMT as well as APEX telescopes and were also obtained from the relevant archives. Additionally, dust temperature and column density maps were obtained from literature and were based on the Herschel space mission observations. First, the maps of the magnetic fields were constructed, their morphology and strengths, as well as gas velocity dispersion maps from the sub-mm spectral observations. Then, the mass-to-flux ratio, Alfvenic Mach number, plasma beta parameter were measured and presented on 2D maps. An extensive discussion of obtained parameters is conducted and the morphology and the state of the molecular cloud is investigated. The strengths of B-field in Oph-A cloud were measured with polarisation and were shown to be in agreement with the results from previous studies, opening a new channel for investigating the morphology of the star-forming clouds. It was also found that the Oph-A cloud is magnetically sub-critical, sub-alfvénic, and gravitationally unbound on a larger scale, but further high-resolution investigations are needed to understand its dynamics in regions hosting dense star-forming structures. The study revealed also that magnetic pressure plays an important role only in some parts of the cloud.

The chapter concludes with an extensive appendix that, in my view, could have been easily integrated into the main body of the chapter.

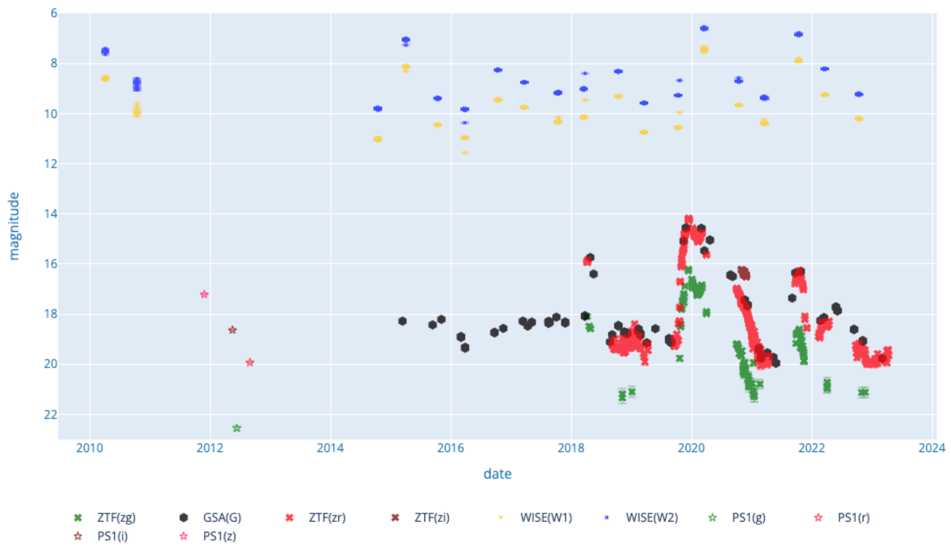
Chapter 4 is based on the publication published by the PhD candidate as the first author in June 2023 and is a study of another cloud, Gy 3-7, which is part of the CMa-l224 region. With the cloud being located in the outer Galaxy, its studies allow probing the impact of metallicity and other environmental factors on the properties of protostars. Again data from SOFIA airborne observatory was used, this time using FIFI-LS IFU instrument. Additionally, data from Herschel as well as Torun's RT4 radiotelescope were also included in this study. I assume the Author has been involved at a significant level in data collection and processing, although it is not entirely clear from the text. The observations were used to determine temperatures, densities and UV radiation field maps of the cloud as well as to identify to which young protostar these properties are linked. The morphology of the cloud was obtained with unprecedented detail for the first time using the distributions of far infrared spectral lines. Parameters of 15 protostars were obtained and it was shown that two of them are indeed YSOs in a very early stage of their evolution. Lastly, it was found that there is no dependence between line cooling and metallicity. The Author concludes the chapter with an outlook of possible future observations necessary to associate YSOs and their outflows with far-IR emissions.

Similarly to Chapter 3, this chapter also features an extensive appendix that could have been, in my view, seamlessly integrated into the main text of the chapter.

Chapter 5 is an observational study of selected Young Stellar Objects (YSOs) in CMa-l224 star-forming region. The content of this chapter is going to be submitted to A&A. It seems this work is part of a larger project led by Dr A. Karska and involves other students and postdocs. This particular work extends the study of YSO sample with new data that allows for more detailed classification and study of their properties. In my opinion, this chapter stands out as the most interesting part of the thesis, highlighting the substantial effort invested by the Author. Nevertheless, there are some noteworthy concerns regarding the analysis and the resulting conclusions.

The new data used in this chapter come from NASA/IRTF telescope and SpeX instrument, which was used to observe 33 YSO candidates, identified based on previous catalogues. It would be good to show an example of IRTF data and their fits when discussing the line fitting procedure, in particular, that it was noted the resolution was not enough to resolve some lines (Section 5.2.1). The study was supplemented with VLT/KMOS data for 8 sources.

It is striking that in the case of some targets observed by both telescopes, there are significant differences in the spectra and lines visible. In particular, G224.3005 shows absorption in CO lines in SpeX data and emission in KMOS data. This was spotted by the Author and is included in the Remarks in Tab. 5.2, however, there is no explanation in the text for this fact. I suspect the difference in spectra is a result of the significant time difference between observations. YSOs are known to vary on timescales of months-years, often showing large outbursts, which exhibit different sets of lines. In the case of G224.3005, in particular, I checked all available archival time-domain data for this target and found the object was observed for many years by mid-infrared space mission NEOWISE as well as optical surveys such as ZTF and Gaia. Below I show the light curve of G224.3005, which exhibited a huge outburst around 2019/2020, close to the time of the IRTF observations. In turn, the data from VLT were collected some time before the flare when the object was in a quiescent state. Note, the flare was visible in both optical and mid-infrared observations and there



were also subsequent flares following the one in 2019/2020. I presume some other targets might also have been affected by the time-variable phenomena and outbursts. This could be one of the main reasons there are some doubts about the re-classification of targets into YSO classes compared to previous analyses.

The observations obtained at different states of the source could have also influenced at least part of the values of parameters. It actually could explain some of the discrepancies visible for example in Fig. 5.8, where the spectral type derived from the Equivalent Width of NaI line is compared to expectations. There is a clear group of targets classified at around K0 spectral type, which does not agree with the spectral library results. This figure would also benefit from showing the error bars on the EW values and I think there should also be a table with EW NaI values and possibly other parameters obtained from the lines along with the error on their measurements.

Table 5.3 misses the error bars on the extinction parameters computed.

The primary objective of Chapter 5, which is to explore the potential relationship between accretion parameters and metallicity, is addressed in subsection 5.5.2. I believe that this section could benefit from further refinement, as the arguments presented do not strongly support the proposed conclusion regarding the absence of such a dependency. The regions of the sky to which the results from CMa-l224 were compared, should be introduced more clearly, stating their metallicity and location in the Galaxy, possibly a simple table would be enough. Furthermore, I do not fully agree with the interpretation of the results shown in Fig.5.10. I think that CMa-l224 and L1641 have similar distributions of accretion luminosities, while other regions like NGC1333 and Lupus show somewhat different distributions. At the end of this subsection, the Author notes that the differences could be induced by some observational biases, however, this is not shown in this chapter if the results here are also affected by such biases and hence if the observed differences are physical or not.

In Chapter 6, the Author provides a comprehensive summary of each chapter. Notably, the summary of each chapter also includes a glimpse into potential future research outlook, especially considering the availability of new instruments such as JWST or CRIRES+.

SUMMARY

Summarising, in my opinion, the PhD candidate has conducted an enormous research work and has done it very carefully and laboriously. The thesis contains a wealth of studies on the subject and has led to new and significant discoveries. The Author has demonstrated a huge proficiency in research through the completion of numerous complex tasks in observational data collecting, data handling, astrophysical analysis, modelling, and interpretation throughout the course of this thesis.

In my view, Ms Ngan Le's work meets all the necessary requirements imposed on PhD theses in Poland, and I, therefore, recommend it for further consideration.

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