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Review of the doctoral thesis of mgr Ngân Thi My Lê entitled "Multi-wavelength observations of the outer Galaxy: Identifying the impact of environment on star formation" (written under the supervision of prof. M. Hanasz and dr A. Karska at Nicolaus Copernicus University)

The Director of the Institute of Astronomy of the Nicolaus Copernicus University presented me with the Ph.D. thesis of mgr N. Lê on the 4th of July 2023. The thesis consists of 138 pages and 6 major chapters, one of which is based in a publication in Astronomy and Astrophysics. The published article and likely other chapters of the thesis were prepared in collaboration with other researchers, but the thesis does not point out which tasks were executed specifically by the Ph.D. candidate. In the following, I am assuming that miss N. Le was the major contributor to the presented work.

The thesis focuses on several aspects of star formation which are currently debated in the astronomical community and therefore provides interesting material in the discussion, especially on the topics of the roles of magnetic fields and metallicity in the star forming regions. The research presented in Chapters 3-5 is relatively original and at places quite unique, like for instance Chapters 3 and 4, which present data from the SOFIA observatory. A big asset of the thesis is a broad range of methodologies used: 1) The analyses presented refer to observational data and techniques in different wavelength regimes from optical to radio wavelengths. 2) A myriad of analysis tools were used, such as spectral energy distribution (SED) fitting, rotational diagrams, PDR modeling, spectral typing, filament identification, etc. Below, I comment on individual chapters of the thesis.

Chapter 1

Chapter 1 is an introductory section of the thesis and presents the scientific background of star formation, introduces the primary astronomical targets discussed in the thesis, and lists a few telescopes and instruments used. The scientific context is formulated in a concise but comprehensive form. I am especially glad to see numerous 'classical' papers being cited rather

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than their modern washed-out derivatives. Miss N. Lê puts special emphasis on the role of magnetic fields in the process of star formation. This is a welcome angle to the scientific background, but, at some places, it lacks the rigorous presentation typical for such introductory materials. For instance, the formulae linking the magnetic field to properties of interstellar matter are presented in scalar form without any explanation of the simplifying assumptions. The naming and notation conventions are not always explained (e.g., whether *SI* versus *cgs* is used, or whether 'magnetic field strength' is used in the meaning of 'magnetic flux density'). When different modern methods of measuring magnetic fields are listed, several important methods were completely neglected, for instance one utilizing the Goldreich-Kylafis effect is not mentioned (but it is mentioned later in Chapter 3). These are, however, only minor shortcomings of the well written Chapter 1.

Chapter 2
Short Chapter 2 introduces the methodology of probing magnetic fields in cool dusty environments, especially in relation to the Radiative Alignment Torques mechanism and the Chandrasekhar-Fermi technique. These are indeed classical models, crucial for modern methods of determining the astronomical magnetic fields. However, I regret, the chapter does not dwell a little bit deeper into the topic of magnetic field measurements, especially on hotly debated problems of B-field determinations depending on the optical depth of the tracer (e.g., dust emission), angular scales, and effects of scattering phenomena. While I appreciate the references to the classical work in the field, modern studies bring a lot to the discussion. That papers like, for instance, the review of Hull and Zhang (2019, https://ui.adsabs.harvard.edu/abs/2019FrASS...6....3H/abstract) are not mentioned worries me that the PhD candidate is not up-to-date with this subfield and its many intricacies.

Chapter 2 also introduces rotational diagrams. After Eq. 2.6 part of the text is missing (definition of the partition function). It would be more elegant if both Eq. 2.8 and Fig. 2.2. used the same type of logarithm (the same is done later in Chapter 4), but it is a minor inconsistency.

In summary, Chapter 2 is a good addition to the thesis but seems relatively unpolished.

Chapter 3
Chapter 3 is very raw and contains many unclear statements. It utilizes archival data, mainly far-infrared polarimetric observations from SOFIA, and relies heavily on results from Santos et al. 2019. The acquired maps are next used to derive different properties of the Oph-A cloud, with a special focus on magnetic fields diagnostics. Properties like magnetic field strength, mass to magnetic-flux ratio, Alfvénic Mach number are derived with multiple simplifying assumptions which unfortunately are not discussed in depth. For instance, it is not discussed why the externally and internally illuminated cloud should have strong coupling between dust and gas temperature. Santos et al. use dust maps as a proxy of hydrogen column density, but miss Ngân Lê decided to

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use the Plummer sphere model to "guess" these densities. It is nowhere explained how densities or number densities of hydrogen were calculated. There are too many unexplained approximations. Although maps from SOFIA at 89 and 154 μm lead to quite different distributions of magnetic field strengths, it is not explained why it is so and how it influences the discussion.

Also, I could not follow the text describing the maps. The morphological features would be better explained if they were labelled in the figures. In particular, I do not see any hourglass shape in the figures of this chapter. Individual vectors can be hardly seen in Fig. 3.1.

Putting aside the confusing presentation and discussions, the Ph.D. candidate demonstrated in this chapter, that she is familiar with the fundamental ideas of cloud collapse and star formation, and can handle relatively complex data processing. The idea to use archival data for this project was very sound.

Chapter 4

Chapter 4 is a very well-polished version of a manuscript which already appeared in Astronomy and Astrophysics, with N. Lê as the leading author. It is the best part of the thesis in terms of content and presentation. The paper demonstrates that the Ph.D. candidate is well versed in modern methodology applied to investigate gas radiative cooling across a wide range of wavelengths. It also presents original material from the SOFIA telescope and the Toruń RT4 radio telescope. The study shows that the PhD candidate understands well the need for comprehensive multi-wavelength observations of different gas and dust tracers to obtain meaningful results.

I found only a few confusing aspects of the chapter. These are just minor comments, mainly related to the paper presentation. One is that there is little to none discussion on the lines' optical depths and how high opacity in the lines would affect the analysis. A related oversight is that none of the observations targeted ^{13}CO transitions (to test the optical depths) and the contribution of ^{13}C to the [C II] profile is not explained. While double profiles of the [C II] far infrared lines are discussed in the context of self-absorption, I was confused what velocity ranges were eventually used to produce moment maps and whether they were consistent for all lines. Both lines of CO J=16→15 shown in Fig. 4.3 appear double, but it is not commented at all. Many maps lack the customary indication of the beam size. A little more in-depth comment is related to the PDR modeling, which requires some assumption of the elemental abundances, but that is not commented on in the study. The abundances are very relevant here, as a region of a supposedly subsolar metallicity was analyzed.

Chapter 5

Chapter 5 is probably the weakest part of the thesis. The presentation of the material is often sloppy, and the text contains many confusing statements and inconsistencies. I was often unsure

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of how the continuum in spectra was handled, because the text mentioned measurements of equivalent widths in continuum-subtracted spectra, which is obviously not right; some figure labels inform about normalized spectra being presented, while clearly those plotted are not normalized.

The aim of the chapter was to constrain reddening and accretion luminosities of several sources, and this is done using several methods which lead to discrepancies as large as above 20 mag in A_V. This is a huge uncertainty which affects all other calculations made in this chapter. Unfortunately, the error propagation is not included in the derived properties such as accretion luminosity. Nevertheless, the derived quantities are compared to other literature data in search for correlations and for indications that star formation at low metallicity differs from that in the Solar neighborhood. Because it is important that an early-career scientist understands the role of uncertainties in the data, I would like miss N. Lê to discuss the uncertainties in the calculated extinction values and their propagation to other quantities derived in Chapter 5.

Chapter 6 is a simple summary with no new content except a brief mention of possible future observations.

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Final opinion

Overall, the thesis of miss M. Le shows that she is well familiar with the methodology used in observational studies aiming to explain star formation phenomena in a very broad context, including the roles of magnetic fields and intrinsic metallicity of the environment. The thesis demonstrates quite convincingly that the Ph.D. candidate is familiar with observations in a wide range of wavelength regimes (from visual to millimeter and radio wavelengths), and can use existing tools to extract meaningful astrophysical information from such data. Chapter 4 convinces me that the Ph.D. candidate can produce a good quality science report which can be useful for the community. Presentation of skills and attention to detail are something miss N. Le needs to work on in her future endeavors.

Given the demonstrated craftsmanship and the broad scope of the dissertation, I am of the positive opinion that the thesis of miss Ngân Lê fulfills the basic requirements posed to obtain the Ph.D. degree in astronomy. Therefore, I recommend the thesis to be defended in front of the respective committee at the Nicolaus Copernicus University in Toruń.

Tomasz Kamiński
29 August 2023, Toruń

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