1. PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan)

Project title:

Variability of the 6.7 GHz methanol masers in high-mass star-forming regions - searching for outbursts and periodic sources

1.1. Project goals

The main goal is to study the 6.7 GHz methanol maser emission which is strongly related to high-mass star-formation in our Galaxy. Single-dish studies give a unique opportunity to monitor the emission and follow its behaviour. Further, it allows us to derive the mechanism of how the high-mass star is being built up. For example, such a method has proved the existence of the phenomena of episodic accretion that was proposed in simulations (Meyer et al. 2017,2019,2021; Burns et al. 2020). Furthermore, systematic and long-term monitoring led to the discovery of periodically variable sources suggesting modulated accretion (Olech et al. 2019,2022). Having a large and consistent sample of more than 100 methanol masers observed with the 32-m antenna over a decade, we propose detailed searches for known and unknown variability behaviour of the maser line. In the case of interesting discoveries, interferometric observations will be proposed to derive their 3D morphology.

1.2. Outline

Studies of high-mass star formation are an important subject of modern astrophysics. These regions are difficult to follow as they are distant and are embedded in dense environments. Therefore, the 6.7 GHz methanol maser emission (the 4.5 cm wavelength in the radio domain), which is observed during the earliest evolutionary phases of high-mass(proto)stars, is a unique tool in such studies. The Torun maser team has been monitoring more than 100 high-mass star-forming regions (HMSFRs) over a decade. The first part of the collected data from 2009-2013 were published by Szymczak et al. (2018) and it has been shown that stable, non-variable sources are not as common as was assumed before. It is high time to summarize the variability of the maser emission systematically observed by the 32-m NCU radio

telescope. Torun's team has discovered HMSFR G107, where water and methanol maser periodically anticorrelate (Szymczak et al. 2016). No other target with such behaviour has been found so far and still, the underlying mechanism is not fully explained since these two molecules and assumed to be pumped in different ways (water collisionally, methanol radiatively). As a member of the international organization M2O (Maser Monitoring Organization), the Torun dish is one out of 4 radio telescopes regularly surveying the sky. In the case of detection of a flare, the multi-frequency studies will start. However, systematic data calibration is needed and that is high time to start a PhD project. The analysis of the data that are available now, will allow to selection new variable sources for further analysis.

1.3. Work plan

1) Analysis and publication of the summary of long-term monitoring observations carried out using the NCU 32-m radio telescope.
2) Identification of new periodic sources.
3) Searching for the outbursts at the 6.7 GHz methanol to enable the international M2O community for follow up observations.
4) Proposing VLBI observations of the interesting targets and modelling the 3D structure of methanol maser emission.

1.4. Literature *(max. 10 listed, as a suggestion for a PhD candidate)*

1) Bartkiewicz A., Sanna A., Szymczak M., Moscadelli L., van Langevelde H.J., Wolak P., Kobak A., Durjasz M., *Proper motion study of the 6.7 GHz methanol maser rings. I. A sample of sources with little variation*, arXiv:2404.07333
2) Burns R.A., Sugiyama K., Hirota T., et al., *A heatwave of accretion energy traced by masers in the G358-MM1 high-mass protostar*, Nature Astronomy, 2020, 4, 506
3) Kobak A., Bartkiewicz A., Szymczak M., Olech M., Durjasz M., Wolak P. et al., *Multi-frequency VLBI observations of maser lines during the 6.7 GHz maser flare in the high-mass young stellar object G24.33+0.14*, Astronomy and Astrophysics, 2023, A135
4) Meyer D.M.A., Vorobyov E.I., Elbakyan V.G., Eisloffel J., Sobolev A.M., Stohr M, *Parameter study for the burst mode of accretion in massive star formation*, Monthly Notices of the Royal Astronomical Society, 2021, 500, 4448

5) Olech M., Szymczak M., Wolak P., Sarniak R., Bartkiewicz A., *6.7 GHz variability characteristics of new periodic methanol maser sources*, Monthly Notices of the Royal Astronomical Society, 2019, 486, 1236
6) Olech M., Szymczak M., Wolak P., Gerard E., Bartkiewicz A., *Long-term multi-frequency maser observations of the intermediate-mass young stellar object G107.298+5.639*, Astronomy and Astrophysics, 2020, 634, A41
7) Olech M., Durjasz M., Szymczak M., Bartkiewicz A., *Detection of periodic flares in 6.7 GHz methanol masers G45.804-0.356 and G49.043-1.079*, Astronomy and Astrophysics, 2022, 661, A114
8) Szymczak M., Olech M., Wolak P., Bartkiewicz A., Gawroński M., *Discovery of periodic and alternating flares of the methanol and water masers in G107.298+5.639*, Monthly Notices of the Royal Astronomical Society, 2016, 459, L56
9) Szymczak M., Olech M., Sarniak R., Wolak P., Bartkiewicz A., *Monitoring observations of 6.7 GHz methanol masers*, Monthly Notices of the Royal Astronomical Society, 2018, 474
10) Szymczak M., Olech M., Wolak P., Gerard E., Bartkiewicz A., *Giant burst of methanol maser in S255IR-NIRS3*, Astronomy and Astrophysics, 2018, 617, A80

1.5. Required initial knowledge and skills of the PhD candidate

The candidate should have knowledge about high-mass star-formation (e.g. Shu et al. 1987) and the basics of radio astronomy. She/he must have the skills in using Python software and a willingness to learn local software to calibrate single-dish data. In the next step, she/he will learn software for interferometric calibrations (AIPS, CASA). It would be appreciated if the candidate has had experiences in single-dish observations and monitoring programs.

1.6. Expected development of the PhD candidate's knowledge and skills

The candidate will be supported by the supervisor and the Torun maser team (Dr. Paweł Wolak and Agnieszka Kobak – PhD student). Also, Prof. Marian Szymczak (emeritus) will be mentoring the candidate and is open for scientific discussions.
Data will be calibrated using the open-source software; the support will be offered. The analysis will be done using the Python program. The

candidate will develop her/his knowledge about high-mass star-formation and the use of single-dish and interferometres like the European VLBI Network.