UNIVERSIDAD NACIONAL AUTONÓMA DE MÉXICO (UNAM)

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STUDY OF COMPACT RADIO SOURCES IN MASSIVE STAR FORMING REGIONS.

PHD THESIS PROTOCOL presented by
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Morelia, Mich., June 2021.

1 Introduction

It is well known that stars are mainly formed, across the whole mass spectrum, in massive star-forming regions. These regions are concentrated in the vicinity of the galactic plane. The early type stars can produce large amounts of ultraviolet radiation that is injected into the surrounding molecular gas, ionizing it and generating HII regions. The observation of the HII regions, specially the Young Stellar Objects (YSOs) in them, is very difficult using optical telescopes due to the protostars been very embedded in large volumes of gas and dust. In this sense, different wavelengths are used to observe this type of objects.

At radio wavelengths we can infer several physical processes that produce two main types of continuum emission mechanisms from the YSOs. They are **thermal emission** and **non-thermal emission**. The first is dominated by the free-free emission which is produced by ionized gas. When they are present around OB stars, these ionized volumes are the so-called ultracompact (UC) and hypercompact (HC) HII regions depending on their density and size (Kurtz 2005). Also, the UV photons of OB stars can ionize the exterior of remaining blobs of neutral gas (Garay et al. 1987). When it is the exterior of protoplanetary disks of young stars the one been ionized, these sources are called proplyds (O'dell et al. 1993; Zapata et al. 2004). Also the ionized winds produced by massive stars are sources of free-free emission (Bieging et al. 1989). Another case comes from jets emanating from accreting protostars of all masses (Anglada 1996; Anglada et al. 2018). In this case the ionization is shock-produced, as opposed to photon-produced as it is the case of the sources previously described.

On the other hand, non-thermal emission can be produced by: gyrosynchrotron radiation due to a young low mass star with magnetospheric activity (Andre et al. 1988) and by the collision of winds from massive binary stars generating synchrotron radiation at the shock region (Pittard and Dougherty 2006).

In the last years, the number of compact radio sources (CRSs) detected in massive star-forming regions has been rising due to the improved receivers and instrumentation installed at radio interferometers. These receivers have allowed us to see additional objects not detected before, specially the most compact and faint objects in the sky. One of the most important updated instruments is the *Very Large Array* (VLA), a radio interferometer located in New Mexico, USA. This update allowed to increase the observed frequency bandwidth and, therefore, increase the instrumental sensitivity, as well as the ability to make observations of the radio-continuum and many spectral lines simultaneously (Perley et al. 2011). Thanks to this, the deep mapping of large areas of the sky and mainly of the galactic plane is currently being carried out. An example of these surveys is the Global View of Star Formation in the Milky Way (GLOSTAR; Medina et al. 2019).

The galactic plane is of main interest since it is where most of the star formation occurs in the Milky Way. For instance, early surveys observed the Orion Nebula finding ~ 20 radio sources of a few mJy of flux (Churchwell et al. 1987; Garay et al. 1987). Several years later, Zapata et al. (2004) increased the cataloged sources to 77 and found that a significant fraction of CRSs shows time variability. Recently, Forbrich et al. (2016) presented the deepest observations ever performed on Orion using the VLA. They detected 556 radio sources of different nature. As a result, there are many studies with the upgraded VLA in other regions such as NGC 6334D to F by Medina et al. (2018) and M17 (Yanza-López et al. in preparation).

In the present work, two regions will be studied using VLA data obtained in 2014. The regions are: NGC 6334A and W3(OH). Early radio maps toward NGC 6334 revealed the presence of six bright compact regions named from A to F (Rodriguez et al. 1982). The study of the compact sources in the D, E and F regions was carried out by Medina et al. (2018), now we will focus on the A region. The distance of NGC 6334 is 1.3 $\pm$ 0.3 kpc (Chibueze et al. 2014) and it is located in the Scorpius constellation. On the other hand, W3(OH) is an UCHII located in the Perseus spiral arm. Its distance is 1.95 $\pm$ 0.04 kpc determined using methanol maser astrometry (Xu et al. 2006). These regions are of special interest since they have peculiar sources that their nature is not understood and these observations will provide new constraints that will help us advance in this problem.

Summarizing, we propose to make an identification and classification of the CRSs associated with HII regions because this allows us to know what is the origin and emission mechanism of them. Besides, the study of different massive HII regions allows us to compare several populations and shed light on the relationship between the emission mechanism and the likely age of the cloud and other important parameters.

2 Goals

Given the conditions described in the previous section, we propose to carry out a study with the main goal of **detecting, identifying, and classifying radio compact sources in different massive star forming regions and determine a relationship comparing their populations.** Once we achieve this objective, we will shed light on the physical processes occurring in the regions, spot how the young stellar population evolves and which are the differences between them. For this, we plan to reach the following specific goals:

1. Learn all the process of calibration and editing (using the VLA pipeline), imaging and self-calibration of the VLA data.

2. Become familiar with the specialized literature on the topic.

3. Identify and analyze the sources, their nature, spectral index, variability, polarization and find the counterparts at other wavelengths. Compare the characteristics of these regions with others previously studied.

4. Analyze the compact sources at the center of the HII regions NGC 6334A and W3(OH).

5. Search for background extragalactic sources that may show plasma scattering and Faraday rotation.

6. Search for galactic gyrosynchrotron sources that will be used for accurate astrometry.

7. Learn the process of making a proposal to an observatory and learn the calibration, editing and imaging of VLBA data.

8. Interpret and discuss our results and report them in two articles submitted to a refereed journal of international circulation.

9. Present these results in a talk at the IRyA, as well as in the National Meeting of Astronomy and in the IAU symposium 361: Massive Stars Near and Far, to take place in Ireland in 2022.

3 Method

In order to achieve the goals specified in the previous section, the following actions will be carried out:

1. **Calibrate the data and obtain an initial map of each region.** The calibration, editing, imaging and self-calibration of the data are handled with the Common Astronomy Software Applications (CASA, a package of several institutions developed for reducing radio interferometric data). The visibilities are calibrated and edited to correct for atmospheric conditions and for the electronics of the receiver. The next step consists in mapping the data using different visibility weightings. In the uv plane, the visibilities are gridded in a two-dimensional lattice. In each pixel of the lattice, we can have zero, one or several visibilities. These visibilities are averaged for each pixel. Natural weighting gives weights to each pixel proportional to the square root of the number of visibilities. Since there is more visibility density at short baselines, this weighting provides modest angular resolution with optimal sensitivity. In the case of uniform weighting, each pixel is given a weight of 1, regardless of the number of visibilities. This weighting is less sensitive but provides better angular resolution and a beam with reduced sidelobes. A compromise between angular resolution and sensitivity can be searched using the robust parameter (Briggs et al. 1999) in the CLEAN task of CASA, which provides an intermediate weighting between uniform and natural. Suppressing the short baselines filters out the extended emission of the region. Finally, if bright enough, the sources falling into our field of view can be used to self-calibrate the data. This technique allows us to increase significantly the dynamical range of the map.

2. **Extract the CRSs from the maps to obtain a catalog.** *BLOBCAT* is a software that runs in python and was developed for extracting sources from astronomical FITS images. It mainly has two important parameters: signal to noise ratio and mesh size. The

former determines the significance of the source detection, while the latter is needed to construct the rms map, necessary for *BLOBCAT* to operate (Hales et al. 2012). This software allows to obtain catalogs with important properties of the sources like: positions, fluxes, angular size, noise, errors, etc.

3. **Identify and analyze the nature of the sources**. The spectral index provides information about the nature of the sources, specifically about their emission mechanism. In general, a negative index means non thermal emission (Rodriguez et al. 1993), while a positive index means thermal emission. Besides, the databases like Vizier or SIMBAD supply information about counterparts at other wavelengths of the sources, e.g. at IR, optical and X ray. The variability and polarization also provide information about the non-thermal nature of the sources. Thus, we can infer the nature of the sources using an analysis of different parameters.

4. **Make new observations**. According to the obtained results from these two regions, we plan to make new observations. First, we will apply proposals to the VLA, in order to observe other massive star forming regions and repeat the same method exposed in points 1, 2 and 3. Second, we will observe specific compact sources from the analyzed regions that contain something peculiar like possible binary nature, bow shock nature, etc. This will be developed using VLBA data.

5. **Compare the populations from different HII regions**. Once the catalogs and the analysis of the nature were obtained, the comparison between the different populations will be carried on to find relationships of the several parameters with the age of the cloud and other parameters.

It is worth to mention that we plan to make internships at the Max Planck Institute for Radio Astronomy (MPIfR), in Germany, and the NRAO, in USA, for knowledge acquisition in this area. Thanks to this, I will be able to make academic relationships for future collaborations.

4 Work Schedule

For the success of our research work we have planned the following tasks (**T**), milestones (**M**) and deliverables (**D**) to perform during the 8 semesters of the PhD thesis work.

T0: Literature reading.

During the duration of the PhD, I will be reading articles related to radio observations in massive star forming regions and emission mechanisms.

T1: Protocol formulation.

D1. Protocol.

T2: Calibrating, editing and self-calibrating the data to obtain the maps toward NGC 6334A and W3(OH).

T2.1. Obtaining the source extraction using BLOBCAT and check the parameters of the detected sources to finally obtain the catalogs from the data.

T3: Prepare an observing proposal to the VLA toward additional regions.

D2. Observing proposal to the Very Large Array.

T4: Spectral index, variability, polarization calculations.

T4.1 Search in databases, like SIMBAD and Vizier, and look for counterparts to the sources in our catalogs at other wavelengths.

T4.2 Analyze the compact sources at the center of the HII regions.

T4.3 Search for background extragalactic sources.

D3. Catalog for each region.

T5: Application exam presentation.

T6: Attend the IAU symposium 361: Massive Stars Near and Far, to take place in Ireland. Later, make a three-months internship to the MPIfR in Bonn, Germany. These plans are conditioned to the pandemic status.

D4. Give talk about the status of the thesis work during the MPIfR internship.

D5. Internship report.

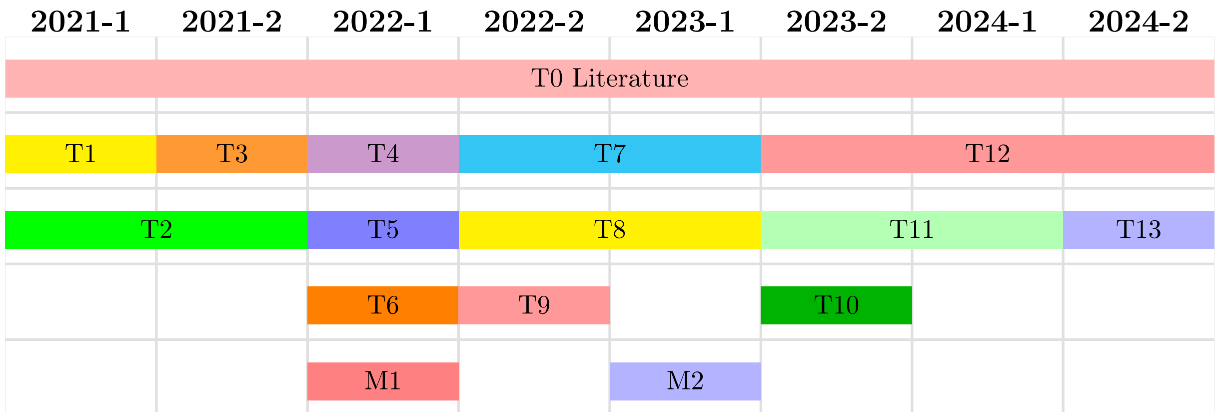
M1: Answer from the observational proposal.

At this point we will have an answer from the Time allocation committee of the VLA regarding the proposal to observe other massive star forming regions. Depending on the answer, we will plan to repeat the procedure carried out for the two regions described above or to resubmit the proposal.

T7: Interpretation of our results through calculations, plots, tables and comparisons to estimate the nature of the sources. Determination of the emission mechanism of CRSs.

T8: Writing and submitting two articles. One of each region.

Work Schedule



D6. Article 1 and 2.

T9: Follow up: Preparing an observing proposal to the VLBA.

D7. Observing proposal to Very Long Baseline Array.

M2: Answer from the observational proposal

Depending on the answer, we will plan to analyze the data or to resubmit the proposal.

T10: Visiting NRAO in Socorro to calibrate new data.

T11: Writing and submitting an article of new VLBA data.

D8. Article 3.

T12: Writing the thesis.

D9. Thesis.

T13: Defense of the thesis

5 Preliminary Results

The calibration and editing, using the VLA pipeline, was applied to the NGC 6334A data in the X band (8-12 GHz). The region contains a bright quasar at the north that make difficult the mapping. Besides, we realized that the flux of the quasar is variable during the time interval of an observation. We restricted our analysis to the first epoch. In order to apply the self-calibration technique to improve the noise of the map, we split the images for each spectral window and scan. We self-calibrate each uv database and then, we concatenate the uv data. The result is

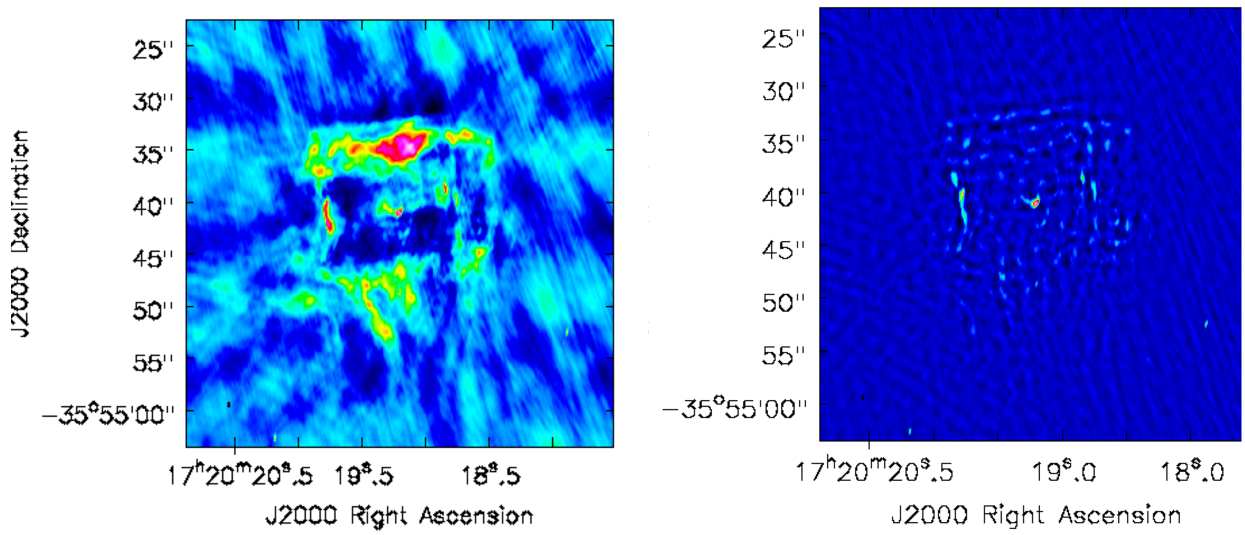


Fig. 1: VLA radio continuum maps toward NGC6334A, using the A configuration and X band for the first epoch. *Left:* Image with all the full visibilities. *Right:* Image cutting the visibilities $< 100k\lambda$.

shown in the Figure 1 Left. The rms noise achieved is 143 μJy/beam and the beam size is 0.57" x 0.14", PA = -9.9°. As we can see the map shows the extended structures associated with the compact HII region. To emphasize the small structure we made a new map discarding baselines shorter than $100k\lambda$ (thus suppressing structures larger than 2 arcsec). The noise achieved in this second map is 57 μJy/beam and the beam is 0.53" x 0.13"; PA= -10.3°. This map is shown in the Figure 1 Right. Zooming in the two maps in the CRS at the center of the NGC 6334A, we can resolve the source. It is worth to mention that it is the first time that this source is resolved. This is shown in Figure 2. As we can see, the source has a shape suggesting a bow shock. Similar structures have been found in other regions containing a binary system of massive stars. In figure 3 we show the example of WR 147. In this source we can see two components. The one to the south is the thermal emission from the wind and the one to the north is the non-thermal bow shock between the two stars in the system.

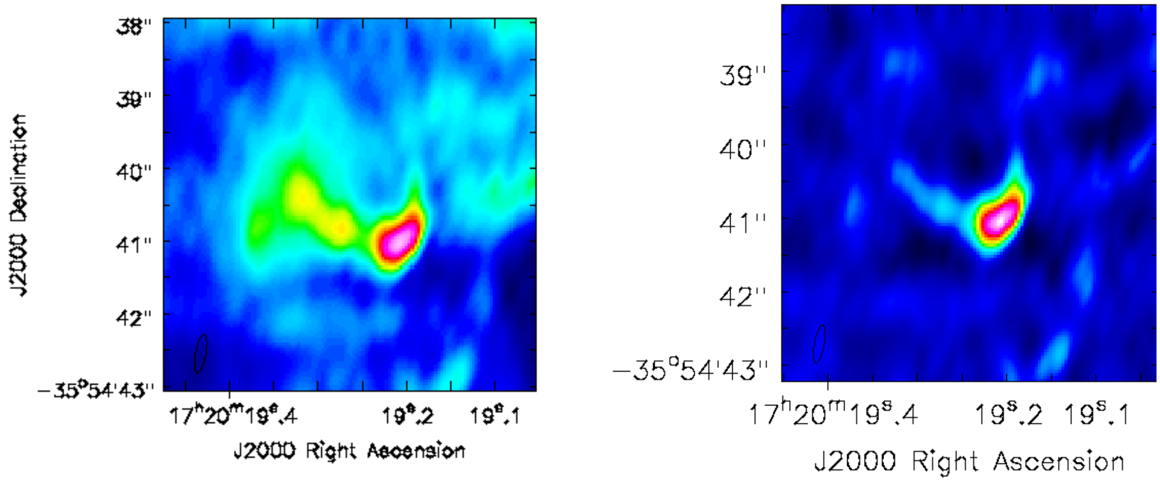


Fig. 2: Similar to Fig. 1, but zooming into the source projected in the center of NGC 6334A.

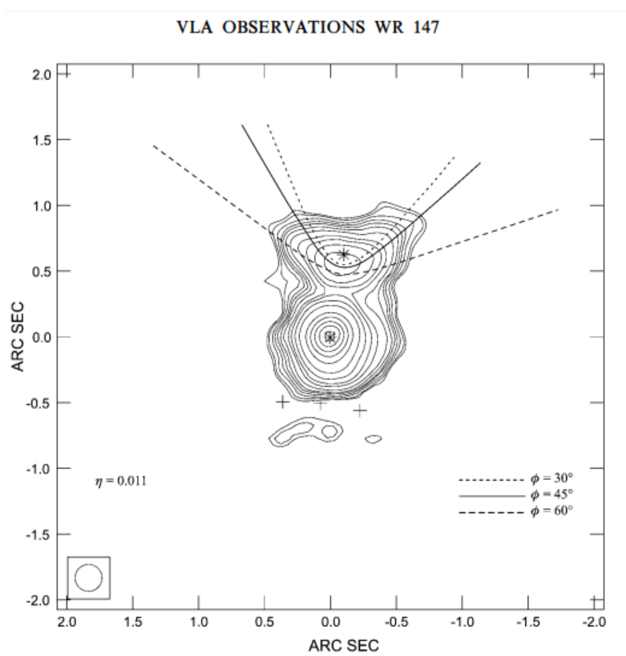


Fig. 3: *Figure taken from Contreras and Rodríguez (1999)*. VLA observations of WR 147. The asterisks mark the location of the two massive stars. The map is centered at the WR 147S position. The set of curves shows the range of possible inclination angles (ϕ) for the bow shock.

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