Discovering CASA:

An Introduction to Imaging Radio Telescope Data

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Abstract

This thesis is an interactive guide designed to introduce researchers to the Common Astronomy Software Applications Package (CASA) for imaging interferomic radio telescope data, particularly data taken by the Atacama Large Millimeter/submillimeter Array (ALMA). The primary objective is to narrow the gap between the complexity of ratio astronomy data processing and the novice researchers' coding skills and understanding. This thesis aims to empower the next generation of scientists in radio astronomy research, fostering discoveries through a more accessible learning environment.

The guide walks users through key concepts in radio astronomy, including functions of interferometers like ALMA and parameters for cleaning data. Using publicly available data from Molecules with ALMA Planet-Forming Scales (MAPS) large program, the users can clean continuum and emission lines data for themselves in a series of Jupyter Notebooks. These activities allow users to engage directly with data processing and build skills for interacting with the data. The guide is publicly hosted on GitHub and can be accessible virtually through myBinder.

1. Introduction

Light interacts with matter in different ways, depending on photon energy. For example, Figure 1 shows how different wavelengths of light, collected by different telescopes, provide information about the Crab Nebula. Dust does not absorb the low-energy radio photons, but optical light is absorbed by dust particles. In the visible light image, filament dust/gas structure is observed, while in the radio regime, the light shows emission from the gas within the nebula. The gamma and X-ray images trace the interactions between the gas and the pulsar at the center of the Crab Nebula.
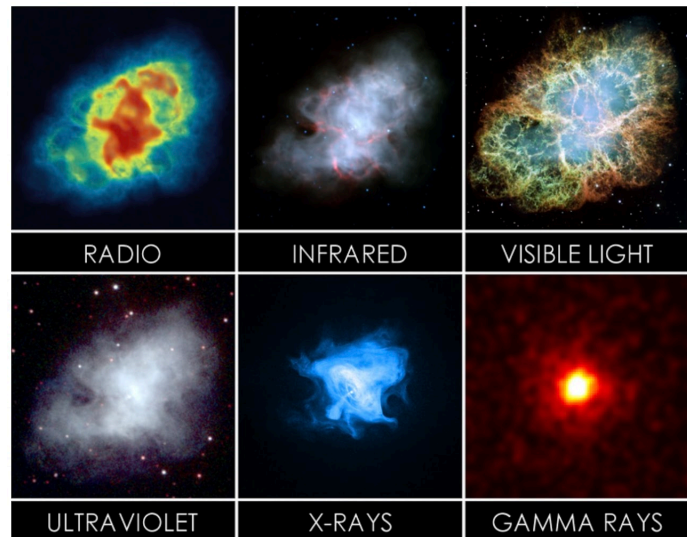

Figure 1: Images of the Crab Nebula in wavelengths spanning the electromagnetic spectrum. Each wavelength tells us something different about the nebula. The radio image was taken by the VLA (credit: NRAO/AUI/NSF). The infrared image was taken by Spitzer (credit:NASA/JPL-Caltech/R. Gehrz University of Minnesota). The visible image light image was taken by Hubble credit: NASA, ESA, CSA, STScI, T. Temim (Princeton University). The ultraviolet image was taken by *Swift* (credit: NASA/Swift/E. Hoversten, PSU). The X-ray image was taken by *Chandra* (credit: NASA/CXC/SAO). The gamma ray image was taken by *Fermi* (NASA/DOE/Fermi LAT/R. Buehler).

Approaching radio astronomy can be daunting for the novice researcher. Observational astronomy across the electromagnetic spectrum is often described to the public as 'taking a picture' of an object in space, but in reality, the data collection process can be complicated. Radio telescopes do not produce images directly, instead light waves are collected as electromagnetic signals (Condon & Ransom 2016) that require further processing methods to generate an image (Thompson et al. 2017, Loomis et al. 2018). Radio astronomers must be adept at transforming these signals into usable images. However, the imaging process requires a great deal of pre-existing knowledge that is not typically taught in a classroom setting, especially courses

taken by early career researchers. I have written an open-source guide[1] to address a potential barrier to accessibility to radio astronomy for the young researcher. This guide provides an interactive introduction to the Common Astronomy Software Applications package (CASA), a tool commonly used to generate images and remove instrumental artifacts from data taken by the Atacama Large Millimeter/submillimeter Array (ALMA).

1.1 Radio Astronomy

Radio astronomy is the study of radio light, photons in the three kilohertz to approximately 900 gigahertz range, originating from astronomical objects (*The Science of Radio Astronomy*, NRAO). Radio light is prevalent throughout the universe because nearly every astronomical object, including the Sun, the galactic center, pulsars, the cosmic microwave background, dust clouds, and planet and star-forming regions to name a few, either emits or absorbs radio light in some manner. Radio observations of these objects provide more information about their size (Andrews et al. 2018), shape (e.g. Huang et al. 2018, Huang et al. 2021, Law et al 2021a,b, Sierra et al. 2021), composition (Öberg et al. 2010, McGuire et al. 2018, McGuire et al. 2020, Scibelli et al. 2020), and motion (Pinte et al. 2020, Teague et al. 2021) in space. Radio astronomy is a key component in mapping the chemical and physical properties of astronomical objects.

Radio astronomy has been used to probe a variety of objects, as big as galaxies and as small as protoplanetary disks. Figure 2 shows the spiral galaxy NGC 6964 in optical and radio light on the same scale (Sancisi et al. 2008). The radio light extends far beyond the bounds of the galaxy in visible light. This indicates that there is gas far beyond the reaches of the inner galaxy

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[1] The guide is publicly available at https://github.com/cat4rcc/CASA_Guide

that shines in visible light. Radio astronomy helps astronomers to better understand the dynamics of galaxies and the star-forming environments they contain. Ground-based radio telescopes like ALMA can probe many of the phenomena that optical and infrared telescopes can not, leading to new discoveries.
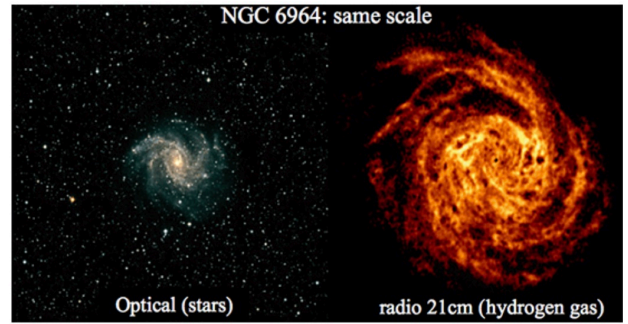

Figure 2: The spiral galaxy NGC 6964, as seen in optical light and radio light. Adapted from Sancisi et al. (2008).

1.1.2 Radio Spectroscopy

Radio astronomy is a powerful tool for identifying gas-phase molecular species. Atoms, ions, and molecules have a spectrum unique to their identity, often referred to as a fingerprint. We can use these chemical fingerprints to learn about the chemical compositions of disks and other objects[2] .

Hydrogen (H_2) is the most abundant molecule in space. In protoplanetary disks, H_2 makes up most of the gas mass. However, H_2 is a symmetric molecule with no permanent dipole moment; it can not be directly detected in space. Carbon monoxide (CO) has a permanent dipole moment and can be detected. CO is the most commonly observed molecule in radio astronomy. CO is considered to directly trace H_2 in a disk, and is therefore often used as a tracer for gas mass (Bolatto et al., 2013, Molyrova et al. 2017). CO detections give astronomers more insight into the evolution of astronomical objects because they can track how the gas mass changes between evolutionary stages.

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[2] See Steinfeld 1974 and Bernath 2016 for further information on this topic.

1.1.3 Interferometers

In an interferometer, a single radio antenna is relatively 'small'. An ALMA antenna is 12 meters in diameter, which when compared to the Green Bank Radio Telescope's 100 meters, are small. However, ALMA consists of 66 antennas, 50 12-meter antennas, and a compact array of four 12-meter and 12 7-meter antennas (known as the ACA) which work together as an interferometer. While the light-gathering power of a single antenna is limited by its diameter, Interferometers consist of many antennas and can collect more light. Interferometers do not observe the sky in the same way a single telescope does. Interferometers miss light that "falls through the gaps" in between the telescopes. In her dissertation, Dr. Waggoner describes an Interferometer as "a single dish with holes in it" (Waggoner, 2024). The placement of the 'holes' effects on the telescope's sensitivity to emitted light and its spatial resolution. The effect of antenna configuration can be seen in Figure 3, which shows how different configurations would view a picture of Dr. Waggoner's cat, Dancer (Waggoner, 2024).
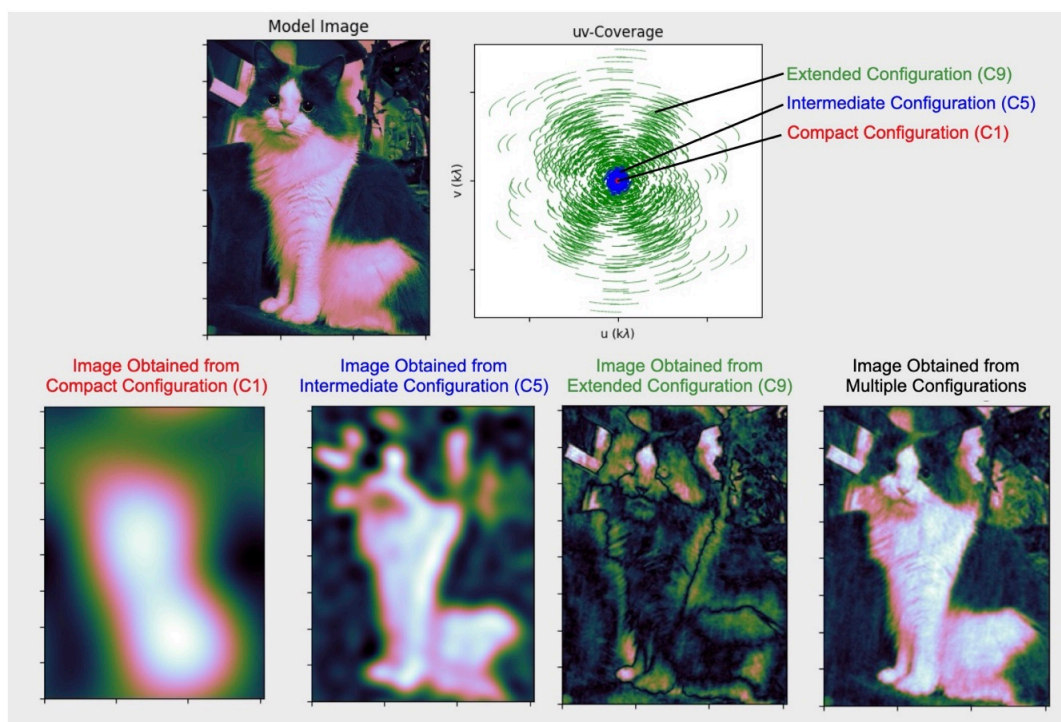

Figure 3: Interferometers introduce artifacts, based on antenna configuration. This figure demonstrates how the model image (the cat, Dancer) would 'appear' in the eyes of an interferometer in three different configurations, extended, compact, and intermediate. Figure taken from Waggoner (2024).

The Common Astronomy Software Applications Package is the primary data processing software for ALMA and other submillimeter/radio interferometers (Common Astronomy Software Applications, n.d.). CASA's primary function is to reconstruct images from the "holey" data obtained by interferometers. However, the nature
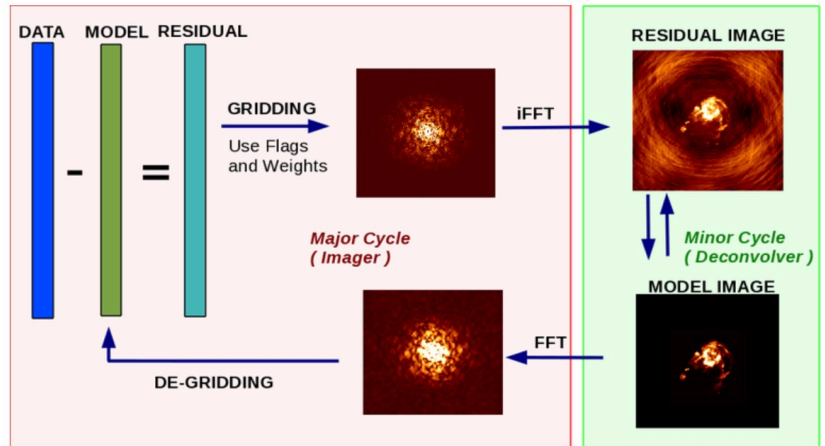

Figure 4: CASA removes artifacts introduced by interferometer by 'cleaning' them. Cleaning happens by removing modeled data from the 'real' data in cyclic iterations until a final image is produced. Image taken from the casatasks guide on `tclean`.

of interferometric data introduces image artifacts, to address this CASA includes a function called `tclean`.

`tclean` works iteratively in two types of stages, the major cycle and the minor cycle, shown in Figure 4. In the major cycle, bright sources are subtracted from the unaltered image, called the dirty image, and then added to a model image. The model image contains all the bright sources that `tclean` has subtracted from the dirty image without any image artifacts. The model image is convolved with the dirty beam, creating an image of what ALMA would see if it imaged only those point sources. The convolved model image is subtracted from the dirty image, leaving fainter point sources and their artifacts. The major cycles, highlighted in the red box in Figure 4, primarily remove bright sources from the dirty image and incorporate them into the model, while the minor cycle removes fainter sources(`tclean`, n.d.).

In the minor cycle, the residual image which contains fainter sources and noise is updated as the faint sources are subtracted from the image. The faint sources are added to the model, refining it to better represent the observation. The model image is then reconvolved and the

process begins again. These cycles repeat until the user-set threshold is met. The `tclean`
process is computationally intense and can take hours to run depending on the size of the data
set, the threshold to which the data is being cleaned, and the computer running `tclean`
(`tclean`, n.d.).

1.2 Motivations

While the official CASA Guides[3] provides a series of tutorials on how to process ALMA
data, the guides do not describe all of the relevant parameters and applications of parameters at a
level accessible to young researchers. The CASA Guides describe the basic processes for
analyzing data, but not why certain parameter values are chosen, or what they mean.

The overall goal of this thesis is to increase accessibility to learning CASA for new
researchers. CASA is a daunting software to approach, and it should be made easier for young
scientists with little to no research experience. Learning how to image data is one of the first
steps in learning how to research astronomical phenomena using radio telescopes. Through
imaging data students are introduced to research applications of radio astronomy and coding in
python.

The guide created for this thesis included a pre-survey, shown in Appendix A. 1, at the
time of writing this thesis, there were six responses recorded. The responses from undergraduate
students at the University of Virginia indicated that students were not familiar with CASA or
radio astronomy research (83% of students indicated no prior experience). When students were
asked about confidence explaining topics relating to radio imaging, overall confidence was low
as shown in Figure 5.

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[3] Official CASA Guides Available at https://casaguides.nrao.edu/index.php?title=Main_Page

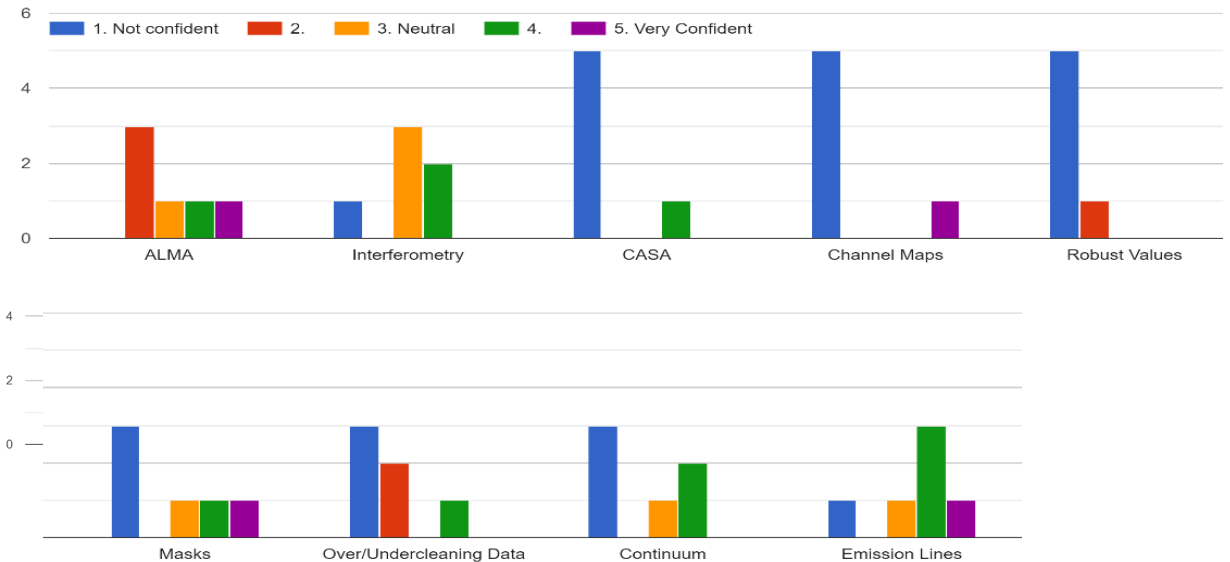How confident are you that you could explain the following topics to a peer?

Figure 5: Pre-survey responses from undergraduate students at the University of Virginia. The survey sought to determine how familiar students are with radio astronomy and related topics. Note that the responses show that most students indicated they are not confident or somewhat not confident in their knowledge of these radio astronomy topics. From the six student responses to the nine questions, 60% of responses indicated a lack of confidence, while only 26% of responses indicated confidence. The Post-survey responses will be incorporated into future work.

This guide works to address the National Radio Astronomy Observatory's mission statement: "Train the next generation of scientists and engineers; Advance broader, equitable, inclusive participation in science and engineering; and Promote astronomy to foster a more scientifically literate society" (NRAO, 2022).

3. Data Selection

The current (5/8/2024) version of the CASA Guide uses data from the Molecules with ALMA at Planet-forming Scales (MAPS) large program. Through the guide students will image data taken of the CO 2-1 transition at 230.538000 GHz. The MAPS data was selected due to its

accessibility and quality.[4] For a guide that is hosted entirely online, having the data available online means that students do not need to download anything on their own computer. The MAPS data is also relatively free of noise and very bright, making it easy to image.

For the guide I imaged MWC 480, a protoplanetary disk shown in Figure 6. I chose to image a protoplanetary disk because it provides students with the opportunity to explore many different aspects of imaging. Protoplanetary disks have a clear structure that can be seen very clearly when observed with ALMA. With a protoplanetary disk students can create spectra, image the dust continuum, image line emission, plot moment 0 maps (i.e. an image integrated over velocity space), and plot channel maps. The disk also has a clear structure that can be imaged, it creates something that is recognizable in the astronomy community.

Figure 6: The MWC 480 protoplanetary disk in CO 2-1 gas (top) and dust continuum (bottom). Both images were developed as a part of MAPS (see Zhang et al. 2021 for CO 2-1 and Sierra et al. 2021 for continuum images)

I selected the CO 2-1 transition data because the CO emission is very bright, and line emission is easily distinguishable due to high signal to noise ratios. CO tends to be one of the brightest emission lines in protoplanetary disks, and is therefore easy to image for a new CASA user. Additional lines (particularly those observed as a part of MAPS) can also be imaged using the guide; however to limit the amount of data downloaded the guide only provides the CO data.
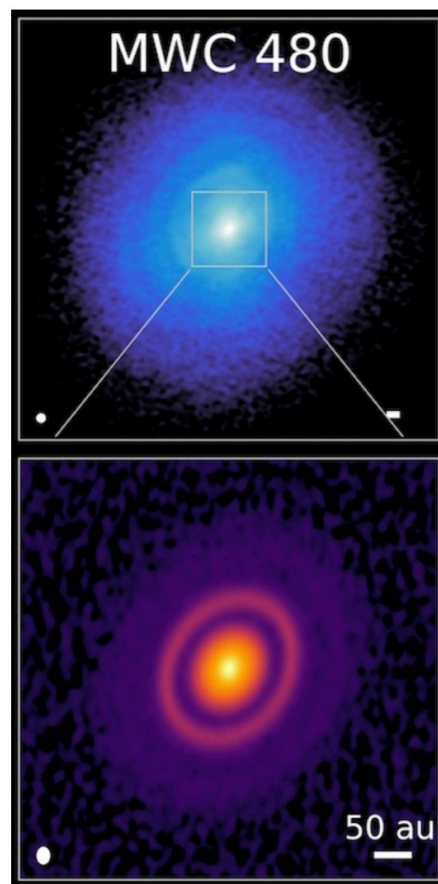
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[4] The MAPS data are available online for anyone's use at https://alma-maps.info/data.html.

4. An Overview of the CASA Guide

The CASA guide consists of four sections in the form of Jupyter notebooks: a set-up, an introduction, an interactive continuum cleaning activity, and an interactive line cleaning activity. These four Jupyter Notebooks work with a host of scripts that are publicly hosted on GitHub. The guide was designed to be used in conjunction with myBinder, which creates an usable python environment from a GitHub repository, so the user can run the Jupyter notebooks within the myBinder virtual machine. The use of myBinder and GitHub allows the guide users to use the guide entirely online without downloading anything new to their personal computers; however the myBinder virtual machine tends to run slowly, so some users may decide to download the repository and work on a personal computer.

4.1 Get Data and Introduction

The first thing that users do is execute 1_GetData.ipynb. This notebook consists of one cell, shown in Figure 7, that uses pip to install python packages `casatools` and `casatasks` as well as other packages required to run the guide successfully. This cell also checks to see if the measurement set that hosts the MAPS data is already installed. If it is not installed, the script gets it from a public Box folder that has the data. The script does the same with the Images folder and the premade masks. After everything has downloaded and installed, the packages are installed in the environment so users can use the guide.

Figure 7: Partial screenshot of the "Get Data" Jupyter Notebook. When executed, this cell downloads packages necessary to run the guide and the measurement sets used in the imaging notebooks.

After downloading all of the packages and files, users are directed to 2_CASAGuideIntro.ipynb. This is the introduction. It is primarily a reading that contains an introduction to radio astronomy and CASA. After reading the introduction, users can start to image the continuum.

4.2 Continuum Cleaning Interactive Guide

In 3_GuideCleanCont.ipynb, the users image the continuum. Users first use the CASA function `uvcontsub_old` to generate the continuum measurement set and continuum subtracted measurement set. The user then generates the dirty image, which is the uncleaned

data. From the Dirty image the cleaning threshold is calculated. With the newly calculated threshold, the user then cleans the data to the indicated threshold. After cleaning the continuum, the user exports the created files including the dirty and clean images and the residuals to fits .files, which they can then plot. In the final cell, the user can display their image (Figure 8) and clearly see the disk structure reported in Zhang et al. (2023) and shown in Figure 6.
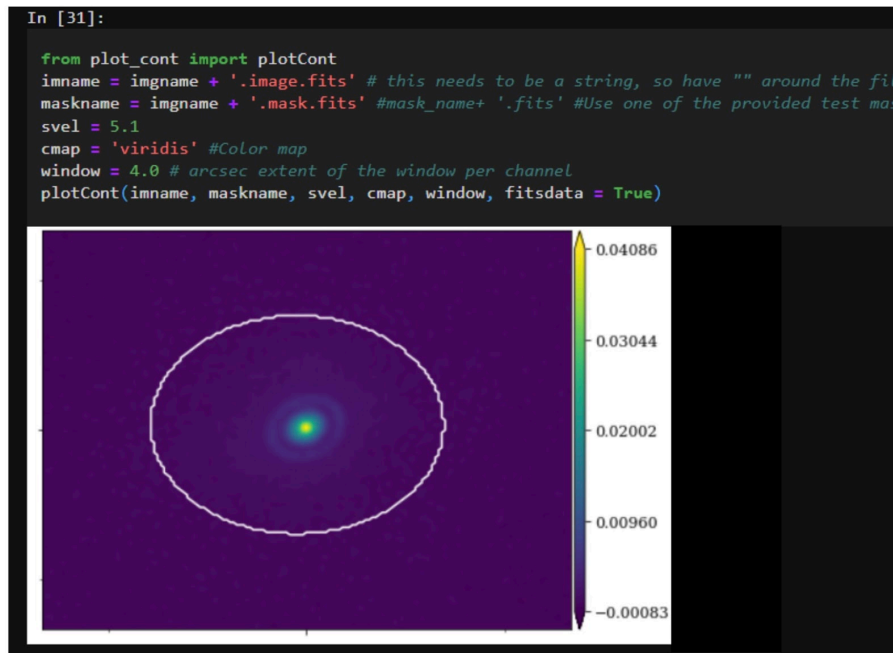

Figure 8: Partial screen shot of the continuum imaging notebook. After the user cleans an image, this cell uses the function `plotCont` (written by C. Thilenius) to plot the continuum with its mask. Note that the continuum image here shows the same substructure reported in Zhang et al. (2021), as shown in Figure 6.

4.3 Emission Line Cleaning Interactive Guide

The final notebook in the guide is 4_GuideCleanLine.ipynb. This notebook contains the line cleaning guided activity. Users are able to follow a similar procedure as used in the continuum imaging, but this time for line emission. First they import the data and set the parameters, again creating the dirty image. From the dirty image, the user calculates the threshold value and cleans to that threshold. After creating the dirty image, the user can plot it

14

quickly as a gif. From the dirty image, the user calculates the threshold and cleans the data to the threshold. The user can then plot a channel map, as shown in Figure 9, showing emission across velocity space, or create a gif showing the channel maps as a movie. The user can plot the residuals as a gif or plot of channels, and conclude the guide by plotting the moment zero map of the data.
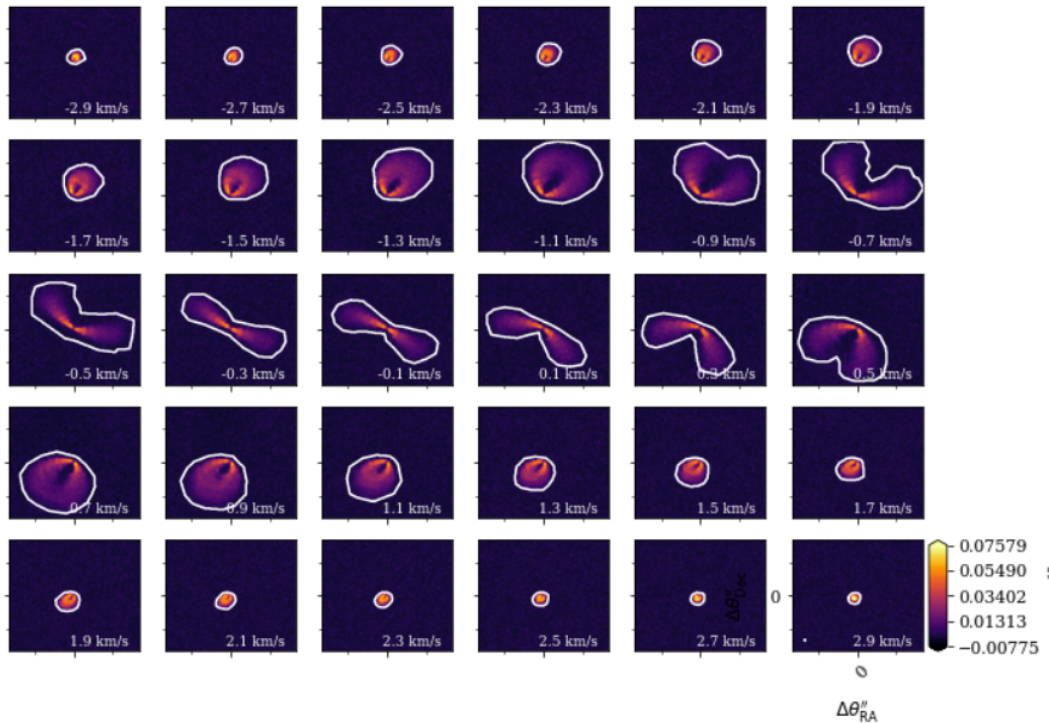

Figure 9: Channel map plotted from the user cleaned data in Line Cleaning notebook. After the user cleans an image, they can use the function `plot_all_V2` (written by C. Thilenius) to plot the channels with its mask. These channels are also plotted as a gif in the guide.

4.4 The Distribution Method

The guide is hosted publicly on GitHub. Users can access it at any time. The user can choose to download the repository to use on their own computer, or they can launch the guide in myBinder. When using myBinder, the python environment is built from the Dockerfile.txt in the repository. myBinder launches the environment in a Virtual Machine. Launching in a Virtual Machine means that the user does not need to download anything to their personal computer,

15

everything is hosted online. Hosting the data online increases accessibility for those who might not have access to a powerful computer, or for those who do not have the space to download large data files.

5. Future Work

While the interactive CASA guide is complete and available for use, its distribution and functionality can still be improved. In future iterations of the guide I will incorporate ideas and changes based on input from user input collected via a post-survey (included in Appendix A.2). There are several more aspects of CASA that could be explored through an interactive guide, like adding a way to extract line spectra from the data set. The guide could also include a section where users can import their own data, other data from MAPS, or data from the ALMA archive. This notebook would allow users to image their data with some helpful tips on how to select parameters like image size, or robust value. The notebook would utilize `automask`, which generates masks based on a user specified threshold within `tclean`. Automasking has already been incorporated in a branch of this guide, but the feature was not included in the final version, since it has not been fully refined.

The MAPS MWC 480 CO 2-1 transition data set is large, and cleaning takes a lot of computing power and time. The guide works when downloaded and runs on the user's computer when the user has enough space and computing power. For those without computing resources, myBinder provides a Virtual Machine where the user can run the guide without downloading anything to their personal computer. However, myBinder's Virtual Machine often times out before the process is complete. I hope to fix this issue by compressing the data set by time

averaging the channels. This might make the guide easier to run on the Virtual Machine, increasing accessibility to the guide.

In the future, I hope that this guide can be used to help undergraduate students better understand imaging radio astronomy data. The astronomy community has already expressed interest in using my guide as a learning tool. For example, Dr. Charles Law is using the guide to introduce interferometry and CASA to an undergraduate summer student, and several others have expressed intent to do so as well. Dr. Samantha Scibelli, a Jansky fellow at the NRAO, has discussed sharing the guide during a lunch talk at the NRAO. Professor Ilsedore Cleeves is considering using the guide in her course Introduction to the Interstellar Medium: Hydrogen to Humans Course taught at the University of Virginia. These are only a few examples of the many ways my guide can be used as an education tool. This thesis aims to empower the next generation of scientists in radio astronomy research, fostering discoveries through a more accessible learning environment in radio astronomy.

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Appendix

A.1 Pre-survey questions

Users are encouraged to complete this pre-survey prior to using the guide. The survey was created as a google form and is available in the GitHub repository as a link in the ReadMe.

CASA Guide Pre-Survey

To be completed before using the CASA Guide.

* Indicates required question

Summary of CASA Guide

This survey is a part of Claire Thilenius's senior thesis. She generated a guide to the imaging tool Common Astronomy Software Applications (CASA), which generates (or cleans) interferometric data, particularly for ALMA. The guide uses an interactive Jupyter Notebook. This pre- and post-survey is meant to measure the efficacy of the CASA Imaging Guide. Acknowledgements will be given to all who complete the surveys, unless they request to remain anonymous.

Any questions or concerns can be directed to Claire Thilenius at cat4rcc@virginia.edu or Abygail Waggoner (thesis advisor) at arw6qz@virginia.edu.

1. Name *

    _____

2. Email *

    _____

3. Would you like to remain anonymous? *

    Check all that apply.

    ☐ Yes
    ☐ No

25

4. I have experience working in a Python environment. *

   Mark only one oval.

   ◯ True
   ◯ False

5. If true, how did you learn Python? What experience do you have?

   _____

   _____

   _____

   _____

   _____

6. I am confident working in Jupyter Notebooks.

   Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

7. I have worked with radio data before (any observing facility). *

   Mark only one oval.

   ◯ True
   ◯ False

8. If yes, what type of data?

   _____

26

9.   I have prior experience with the imaging tool CASA. *

Mark only one oval.

◯ Yes

◯ No

10.   If yes, how did you learn to use CASA and what experience do you have?

_____

_____

_____

_____

_____

11.   I am confident in my ability to image ALMA data using CASA. *

Mark only one oval.

          1   2   3   4   5

Stro ◯ ◯ ◯ ◯ ◯ Stronogly Agree

12.   I am confident in my ability to generate images from interferometric radio data *
(like ALMA data).

Mark only one oval.

          1   2   3   4   5

Stro ◯ ◯ ◯ ◯ ◯ Strongly Agree

27

13. How confident are you that you could explain the following topics to a peer? *

Mark only one oval per row.

	1. Not confident	2.	3. Neutral	4.	5. Very Confident
ALMA	◯	◯	◯	◯	◯
Interferometry	◯	◯	◯	◯	◯
CASA	◯	◯	◯	◯	◯
Channel Maps	◯	◯	◯	◯	◯
Robust Values	◯	◯	◯	◯	◯
Masks	◯	◯	◯	◯	◯
Over/Undercleaning Data	◯	◯	◯	◯	◯
Continuum	◯	◯	◯	◯	◯
Emission Lines	◯	◯	◯	◯	◯

28

A.2 Post-survey questions

Users are encouraged to complete this post-survey after using the guide. The survey was created as a google form and is available in the GitHub repository as a link in the ReadMe.

CASA Guide Post-Survey

To be completed after completing the CASA Guide.

This survey is a part of Claire Thilenius's senior thesis. She generated a guide to the imaging tool Common Astronomy Software Applications
(CASA), which generates (or cleans) interferometric data, particularly for ALMA. The guide uses an interactive Jupyter Notebook. This pre- and post-survey is meant to measure the efficacy of the CASA Imaging Guide. Acknowledgements will be given to all who complete the surveys, unless they request to remain anonymous.

Any
questions or concerns can be directed to Claire Thilenius at cat4rcc@virginia.edu or Abygail Waggoner (thesis advisor) at arw6qz@virginia.edu.

* Indicates required question

1. Name *

    _____

2. Email *

    _____

3. Would you like to remain anonymous? *

    Mark only one oval.

    ( ) Yes

    ( ) No

30

4. I am confident in my ability to image ALMA data with CASA. *

    Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

5. I am confident in my ability to work in Python environment. *

    Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

6. I am confident in my ability to generate images from interferometric radio data (like ALMA data).

    Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

31

7. How confident are you that you could explain the following topics to a peer? *

Mark only one oval per row.

	1. Not Confident	2.	3. Neutral	4.	5. Very Confident
ALMA	◯	◯	◯	◯	◯
Interferometry	◯	◯	◯	◯	◯
CASA	◯	◯	◯	◯	◯
Channel Maps	◯	◯	◯	◯	◯
Robust Values	◯	◯	◯	◯	◯
Masks	◯	◯	◯	◯	◯
Over/Undercleaning Data	◯	◯	◯	◯	◯
Continuum	◯	◯	◯	◯	◯
Emission Lines	◯	◯	◯	◯	◯

8. What did you learn form this tool? *

_____

_____

_____

_____

_____

32

9. What was confusing, needs clarification, or what can we do to make the guide   *
    more stronger?

    _____

    _____

    _____

    _____

    _____

10. If you are familiar with CASA, would this tool have been helpful while you were
    learning? If you are not familiar with CASA, was this guide useful?
    Why or why not?

    _____

    _____

    _____

    _____

    _____

11. Any additional comments?

    _____

    _____

    _____

    _____

    _____

33