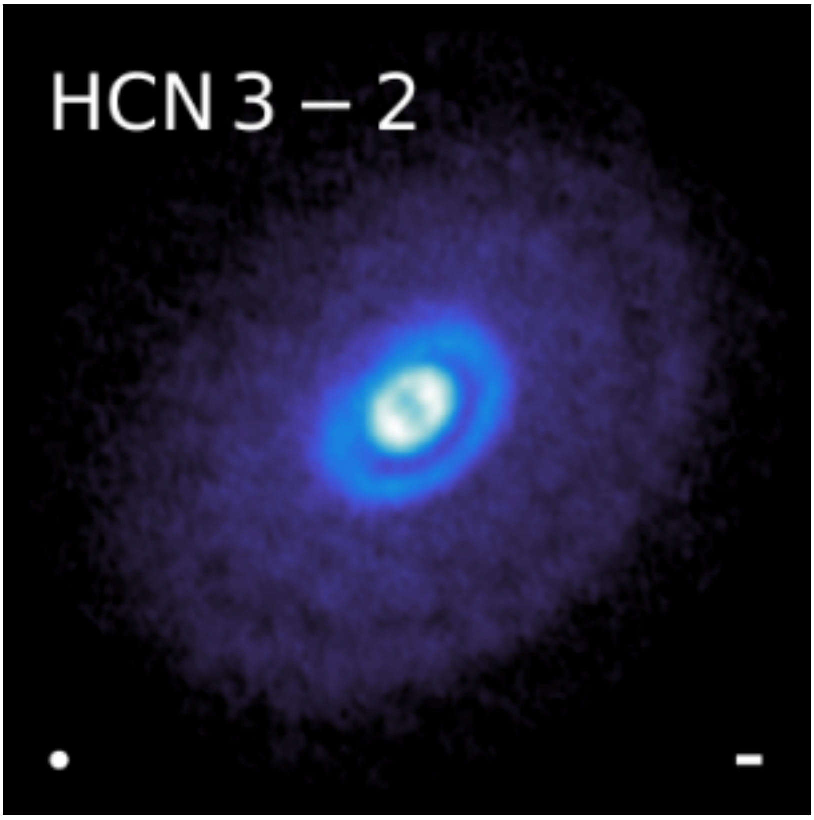
Imaging and analysis of molecular line emission from protoplanetary disks

Dustbusters Summer School 2022

Catherine Walsh & John Ilee
University of Leeds, UK



Moment 0 map of the HCN 3-2 rotational transition from the disk around HD 163296 at a spatial resolution of 0.15" (Oberg & MAPS Team, 2022, ApJS, 257, 1).
www.alma-maps.info

This project will involve a demonstration of how to image ALMA observations of molecular line emission from a protoplanetary disk. We will guide you through the data analysis conducted on these images including the derivation of data products such as line intensities, line profiles, and radial profiles. Using multiple lines from the same molecular species we will also provide instructions on how to empirically extract properties from the data such as the column density of the species and the rotational (excitation) temperature. You will gain skills in data imaging and analysis specific to protoplanetary disks, but some of which is more generally applicable to other astrophysical environments. *Software required: CASA, python*

1. Download of software and tools

You will need a working installation of python 3.x and pip.

You will need the most recent version of CASA that works with your operating system:

> CASA 6.x - https://casa.nrao.edu/casa_obtaining.shtml
> How to install - https://casa.nrao.edu/casadocs/casa-6.1.0/usingcasa/obtaining-and-installing

It is also recommended to install casatasks for use of several casa functions outside of the casa terminal (most useful for the analysis step):

> casatasks - https://pypi.org/project/casatasks/#description -> pip install casatasks

You will also need some additional analysis tools for imaging and analysis:

> Analysis Utils - https://casaguides.nrao.edu/index.php/Analysis_Utilities
> gofish - https://fishing.readthedocs.io/en/latest/ - > pip install gofish
> better moments - https://bettermoments.readthedocs.io/en/latest/ -> pip install bettermoments

We will also use an updated version of the Reduction Utils scripts developed by the DSHARP collaboration - https://almascience.eso.org/almadata/lp/DSHARP/scripts/reduction_utils.py

> reduction_utils.py

This will be in the download package.

Before proceeding with the next steps, make sure that you can open casa, casaviewer, and casaplotms from the command prompt. Also check that you can run the commands and routines provided in the analysis and reduction utilities scripts from within a casa environment. You can import these scripts via creation of a casa start-up file ~/.casa/startup.py.

2. Download of project materials

For the analysis step of the project, we will be working directly with image cubes produced by the ALMA Large Program, MAPS (Molecules with ALMA on Planet Forming Scales; www.alma-maps.info). However, because of the time and computational power needed to reduce these data, for the imaging step of the project, we will work with a tutorial measurement set provided by ALMA for the disk around TW Hya.

Once the group members are assigned, Catherine will e-mail you a link to download all the project materials.

3. *Project steps*

3.1 Data imaging step

Download the already calibrated science verification Band 7 data for TW Hya. The original data can be obtained from https://almascience.eso.org/almadata/sciver/TWHya/ but we provide the data all in one place for convenience:

> TWHYA_BAND7_CalibratedData.tgz (5.7 GB)

We will follow a similar imaging procedure as the tutorial https://casaguides.nrao.edu/index.php?title=TWHydraBand7_Imaging_4.3 but we provide a bespoke self-calibration and imaging script for you to follow which is based on that done for MAPS:

> P1_imaging_script_student.py

This step will give you a broad understanding of the process of self-calibration and imaging of molecular line data using a reasonably-sized dataset. Modern ALMA datasets require processing on powerful workstations and/or clusters, especially those that combine multiple executions and multiple array configurations. The end result of the imaging step will be three images: one continuum image, and two spectral line cubes for the CO 3-2 rotational transition and the HCO^+ 4-3 rotational transition.

3.2 Data analysis step

Depending on the project group that you are in, download the already imaged cubes for **either HD163296 or MWC480** for the HC_3N 11-10 and 29-28 transitions, and which are also available at the MAPS team webpage (https://alma-maps.info/data.html). Again we provide the data all in one place for convenience:

> HD_163296_HC3N_90GHz.0.3arcsec.JvMcorr.image.pbcor.fits
> HD_163296_HC3N_260GHz.0.3arcsec.JvMcorr.image.pbcor.fits

> MWC_480_HC3N_90GHz.0.3arcsec.JvMcorr.image.pbcor.fits
> MWC_480_HC3N_260GHz.0.3arcsec.JvMcorr.image.pbcor.fits

We will use the data imaged at 0.3" resolution with primary beam and JvM correction applied (*.JvMcorr.image.pbcor.fits). We choose this resolution to ensure a homogeneous resolution for the data in Band 3 and Band 6. We also provide the mask used for cleaning the data (*.0.3arcsec.mask.fits) for interest.

We will follow a similar analysis procedure as outlined by the MAPS team:

> Law et al. 2021, ApJS, 257, 3
> Ilee et al. 2021, ApJS, 257, 9

We will produce the so-called "value-added data products" (VADP).

For each transition we will:
> conduct visual examination of the spectral cubes
> estimate the signal-to-noise ratio in the spectral line cubes
> produce moment 0 (integrated intensity), 1 (intensity-weighted velocity), and 8 (peak intensity) maps
> extract the disk-integrated line profile and line flux
> produce a radial profile of the emission

We provide a bespoke outline script to conduct these analyses:
> P1_analysis_script_student.py

3.3 Rotation diagram

Once the disk-integrated line fluxes are measured for both transitions, we will perform a rotational diagram analysis to empirically determine the disk-averaged rotational temperature and column density of HC_3N in the disk. We will use the methodology outlined in:

> Loomis et al. 2018, ApJ, 859, 131
> Ilee et al. 2021, ApJS, 257, 9

Once again we provide an outline script:
> rotation_diagram_script.py

You only need to modify the information at the bottom of this script before running. You will need the disk-integrated fluxes and estimated errors from the two transitions done in the analysis step.

Compare your disk-average column densities and rotational temperatures with those from Ilee et al. (2021).

4. *Further work*

If you and your team get through the above well ahead of the time allocated for project work during the summer school, there are several additional steps you can take:

> you can perform a similar analysis on another MAPS dataset: https://alma-maps.info/data.html
> for example, you could do the same analysis on brighter lines, e.g., HCN
> you can download some data products from the ALMA archive for a different disk/line transition

As an alternative, for those that are interested:

> you can have a go at some astrochemical modelling of HC3N in protoplanetary disks

If you would like to do the latter, make contact with Catherine who will supply you with some codes and template disk models to compute the chemistry.