GISM3 SUMMER SCHOOL

List of Hands-on Projects

Contents

Project 1 Cosmic rays interaction with interstellar dust grains

Supervisor: Emmanuel Dartois (ISMO, Orsay, France)

Objectives:

1. Learn to calculate energy deposited by cosmic rays in matter.
2. Learn how to transpose laboratory experiments to dust grain damage in the ISM.

Description:

1. Use of a software to calculate the Stopping and Range of Ions in Matter, energy deposited. You need to install a Windows based package SRIM/TRIM, SRIM2013 package which can be found at http://www.srim.org/SRIM/SRIMLEGL.htm. If you do not have windows or an emulator, if a few students can have it, we will share the outputs at the beginning of the sessions, and retrieve some data that will be used afterwards as inputs with your favourite coding system.
2. Using ISM CR abundances, determine ionisation rates (needs to program with your favorite system).
3. Using lab experiments destruction cross sections measured as a function of stopping power, determine carbon grains lifetimes.

Project 2 Spectro-photometric SED fitting of star forming galaxies

Supervisor: Patrice Theulé (LAM, Marseille, France)

Description. During this project the student will use the Sings/KINGFISH sample of nearby galaxies (Dale et al. ApJ 2017) and fit their spectral energy distribution (SED) using the CIGALE SED fitting code. The students will learn to use the different CIGALE modules to simulate physical inputs (star formation history, dust attenuation,...) to generate photometric ans spectroscopic data to fit against the observational sample to retrieve the physical parameters governing galaxy evolution (gas mass, stellar mass, age, ...). In addition, the students will learn how to generate the nebular emission lines stored in CIGALE using the CLOUDY photoionization code. Then they will build a BPT diagram using strong emission line ratios to discriminate between star forming galaxies and active galaxies nuclei.

Project 3 Tracing the physical properties of warm molecular gas through observations and models of the submillimeter CO rotational ladder

Supervisors: Miriam G. Santa-María & Javier R. Goicoechea (IFF-CSIC, Madrid, Spain)

Description: In star-forming galaxies, UV radiation from massive stars heats the molecular gas to warm temperatures and creates photodissociation regions (PDRs) at the illuminated rims of molecular clouds and at large spatial scales. Finding observational probes of this radiative feedback is highly relevant. Emission lines from the CO rotational ladder are among these probes and serve as excellent diagnostics of the gas's physical conditions. In particular, they are useful 'thermometers' for determining the gas temperature. In this hands-on session, we will analyze a set of high-spectral-resolution $^{12}C^{16}O$ J=4–3 to J=16–15 line observations (along with $^{13}C^{16}O$ and $^{12}C^{18}O$ line detections) of the prototypical dense and strongly illuminated PDR, the Orion Bar, observed with the Herschel Space Observatory. In particular, we will:

1. Explore the submm spectra.
2. Extract line profile parameters.
3. Build and interpret rotational population diagrams.
4. Analyze the observed line intensities using non-LTE excitation and radiative transfer models.
5. Study the predictions of more sophisticated PDR models.

This exercise will allow students to manipulate submillimeter line observations, understand the subtleties of non-LTE molecular excitation, and become familiar with public tools used to interpret observations of the CO rotational ladder from local PDRs to high-redshift galaxies.

Bibliography:

- Goldsmith & Langer 1999, ApJ, 517 (Rotational diagram)
- Le Petit et al. 2006, ApJS, 164 (Meudon PDR code). Non exhaustive reading needed.

Software:

- Install GILDAS/CLASS https://www.iram.fr/IRAMFR/GILDAS/ or any software to handle spectra and Gaussian line fits.
- RADEX on-line: https://var.sron.nl/radex/radex.php
- Installing RADEX off-line if you prefer fortran https://sronpersonalpages.nl/ vdtak/radex/index.shtml
- We suggest to install the python-based package `ndradex`: https://pypi.org/project/ndradex/

Project 4 Black bodies but not black boxes – variations on fitting dust SEDs

Supervisors: Frédéric Galliano (AIM, CEA Paris-Saclay, France) & Annie Hughes (IRAP, Toulouse, France)

Objectives:

- Learn how to perform least-squares fitting and Bayesian inference without relying on black boxes.
- Learn about *Spectral Energy Distribution* (SED) fitting and dust physics.

Description: This hands-on will be divided into two main parts.

Part I. DIY SED fitting: in this first part, we will consider the simplest dust SED model, the *Modified Black Body* (MBB). This will allow us to momentarily put aside the inherent complexity of dust physics to focus on the different techniques for fitting such models to broadband *InfraRed* (IR) photometry of galaxies. We will propose the participants to implement their own least-squares and Bayesian fitters. We will also demonstrate how to interpret *Markov Chain Monte Carlo* (MCMC) results and how to handle model degeneracies. Our hope is that this SED fitting work-out, applied to a simple case, will provide the participants with a more fundamental understanding of model inference and thus help them dealing with the epistemic opacity of more advanced codes, that could otherwise appear as black boxes.

Part II. Using DustEM: in this second part, we will consider more realistic dust models, mainly THEMIS (Jones et al., 2017), through the DustEM interface. We will perform *sensitivity analysis* to understand the different degeneracies between parameters such as the fraction of small grains and the hardness of the interstellar radiation field. We will then use DustEMwrap to produce maps of the dust properties from a collection of multi-wavelength images of a nearby galaxy.

Overall, we will adapt the content of this hands-on to the skills and interests of the participants.

Software:

- We will mainly work in Python 3, using various easy-to-install modules (`numpy`, `scipy`, `emcee`, *etc.*).
- In the second part, we will also use DustEM and DustEMwrap. This will require installing GDL.

Bibliography:

- Galliano (2022), HDR, Université Paris-Saclay, Chapter V: PDF or HTML
- Jones et al. (2017), A&A, 602, A46

Project 5 CNO Abundance Analysis in Nearby Galaxies Using UV–Optical Spectra

Supervisor: Danielle Berg (University of Texas, Austin, USA)

Description: In this hands-on project, students will perform a complete chemical abundance analysis of one or more star-forming regions in nearby galaxies using UV–optical emission-line spectroscopy. Working with real spectra, students will measure key diagnostic lines, determine electron densities and temperatures, calculate ionic abundances, apply ionization correction factors, and derive total oxygen, nitrogen, and carbon abundances. The project will conclude with interpretation of the results in the context of observed C/O–O/H and N/O–O/H trends in the local universe. By the end of the week, students will have constructed a fully empirical picture of the ionized gas conditions in galaxies and will present their findings in a short group presentation.

Project 6 Machine learning techniques to turn rotational lines into powerful diagnostics of the physical conditions inside a Giant Molecular Cloud – The Orion B case

Supervisors: Laure Bouscasse & Jérôme Pety (IRAM, Grenoble, France)

Context: Molecules have long been thought to be versatile tracers of cold neutral media in the universe, from high-redshift galaxies to star forming regions and proto-planetary disks, because their internal degrees of freedom are controlled by physical conditions in their environments. However, the promise that molecular emission has a strong predictive power of the physical and chemical state of the interstellar medium is still hampered by the incomplete understanding of the complex physical and chemical structure of the interstellar gas, and its dynamical evolution. The ORION-B project (Outstanding Radio-Imaging of OrioN-B, co-PIs: J. Pety and M. Gerin) is a Large Program of the IRAM 30m telescope that aims to improve the understanding of physical and chemical processes of the interstellar medium by mapping a large fraction of the Orion B molecular cloud (5 square degrees) with a spatial resolution of 27" (50 mpc at a distance of 400 pc) and a spectral resolution of 200 kHz (or 0.6 $km\,s^{-1}$) over the full 3 mm atmospheric band (72 – 116 GHz).

All this is subject to discussion with the students in order to follow their interest. We expect the student to work in teams in order to deliver a unified presentation of 10 minutes at the end of the school to explain what they did.

Objectives: In this hands-on activity, we will use part of the ORION-B data:

1. To perform deep learning denoising of the data using neural network encoders.
2. To define an estimator of the column densities from the molecular line data.

Foreseen activities:

- Presentations, description of the project, getting the data and the software.
- Visualization of data, computation of noise, moments.
- Deep learning denoising by dimension reduction of molecular line cubes to increase their signal-to-noise ratio. This will use a taylored python package.
- Using the Principal Component Analysis to highlight the correlations between the gas column density and the molecular line integrated intensities.
- Using random forests to learn the relation between line integrated intensities and the column density of molecular gas.

Software:

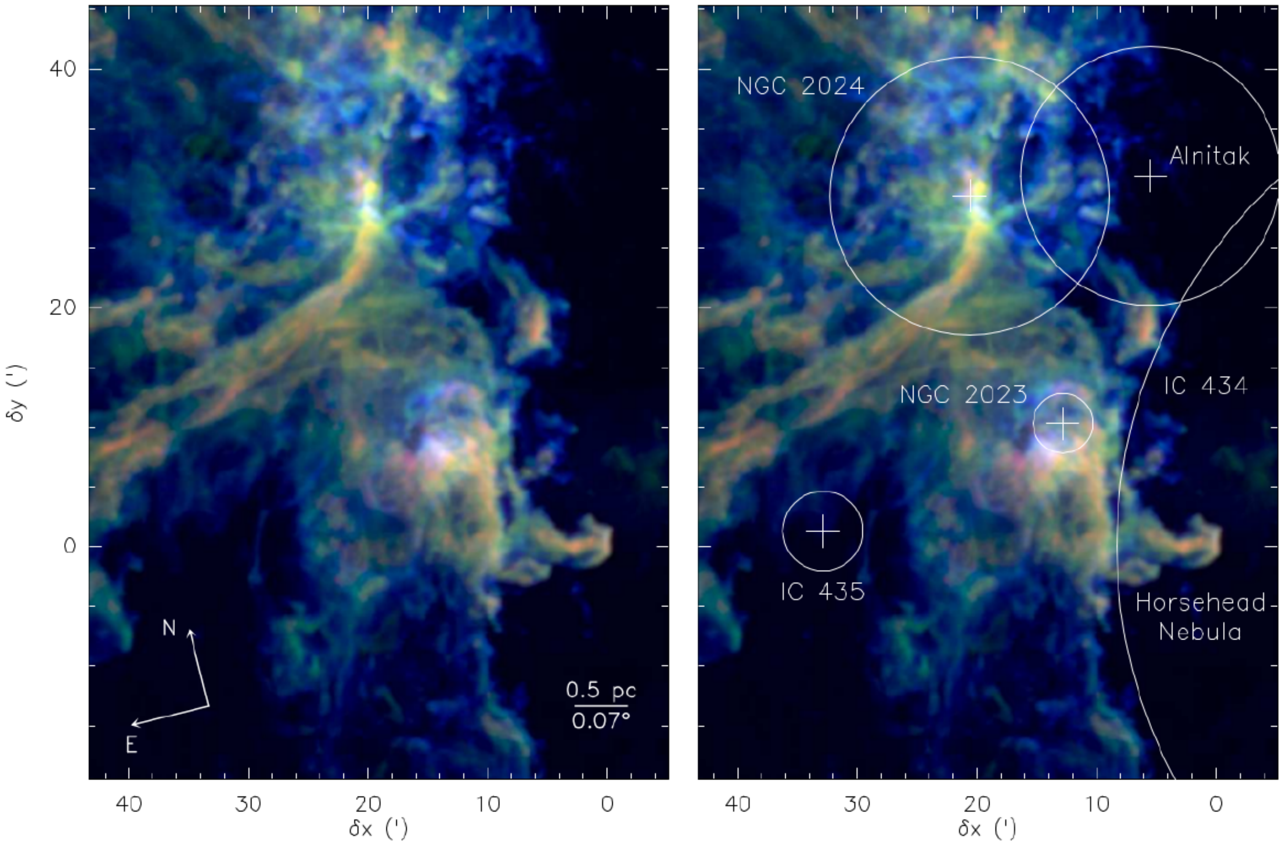
- https://github.com/einigl/line-cubes-denoising

Bibliography:

- *Quantifying the informativity of emission lines to infer physical conditions in giant molecular clouds. I. Application to model predictions*, Einig et al., A&A, 2024, doi:10.1051/0004-6361/202451588.
- *Bias versus variance when fitting multi-species molecular lines with a non-LTE radiative transfer model*, Roueff et al., A&A, 2024, doi:10.1051/0004-6361/202449148.
- *Neural network-based emulation of interstellar medium models*, Palud et al., A&A, 2023, doi:10.1051/0004-6361/202347074.
- *Deep learning denoising by dimension reduction: Application to the ORION-B line cubes*, Einig et al., A&A, 2022, doi:10.1051/0004-6361/202346064.
- *Revealing which Combinations of Molecular Lines are Sensitive to the Gas Physical Parameters of Molecular Clouds. Astrophysics Meet Data Science towards the Orion B Cloud*, Pety et al., EPJ Web of Conferences, 2022, doi:10.1051/epjconf/202226500048.
- *Learning from model grids: Tracers of the ionization fraction in the ISM*, Bron et al., EPJ Web of Conferences, 2022, doi:10.1051/epjconf/202226500023.
- *Quantitative inference of the H_2 column densities from 3 mm molecular emission: A case study towards Orion B*, Gratier et al., A&A, 2021, doi:10.1051/0004-6361/202037871.
- $C^{18}O$, ^{13}CO, and ^{12}CO abundances and excitation temperatures in the Orion B molecular cloud: An analysis of the precision achievable when modeling spectral line within the Local Thermodynamic Equilibrium approximation, Roueff et al., A&A, 2021, doi:10.1051/0004-6361/202037776.

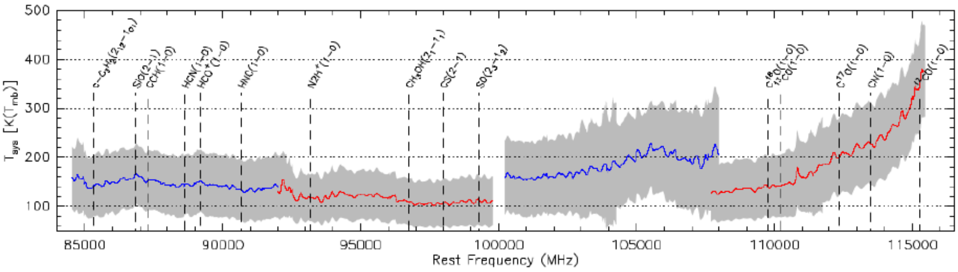
- *Tracers of the ionization fraction in dense and translucent gas: I. Automated exploitation of massive astrochemical model grids*, Bron et al., A&A, 2021, doi:10.1051/0004-6361/202038040.
- *Clustering the Orion B giant molecular cloud based on its molecular emission*, Bron et al., A&A, 2018, doi:10.1051/0004-6361/201731833.
- *Dissecting the molecular structure of the Orion B cloud: Insight from Principal Component Analysis*, Gratier et al., A&A, 2017, doi:10.1051/0004-6361/201629847.
- *The anatomy of the Orion B Giant Molecular Cloud: A local template for studies of nearby galaxies*, Pety et al., A&A, 2017, doi:10.1051/0004-6361/201629862.

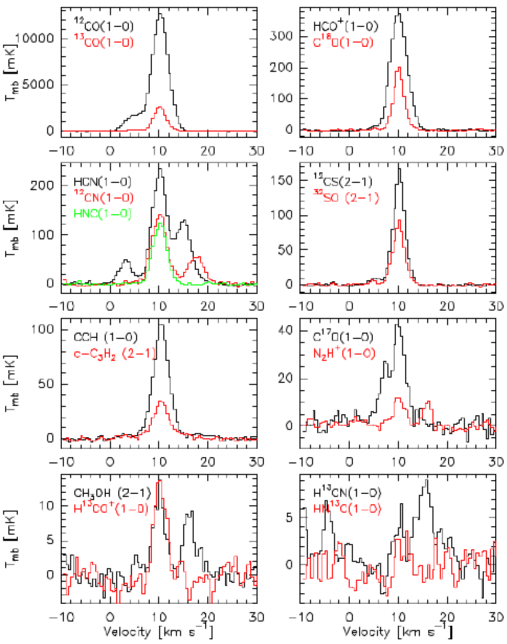
Studied filed of view

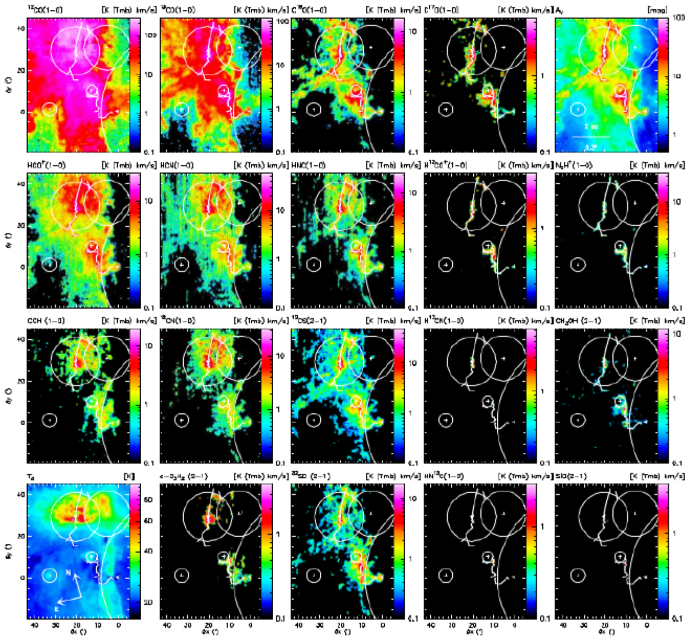


$C^{18}O$ (J=1–0), ^{13}CO (J=1–0), ^{12}CO (J=1–0)

Data at a glance







Project 7 Spreading metals in the ISM

Supervisor: Donatella Romano (INAF, Bologna, Italy)

Description: We will use a customized version of the adaptive mesh refinement hydrodynamical code RAMSES (Teyssier 2002) to perform idealized simulations that will study how different elements produced by different types of stars spread in the ISM of galaxies.

Project 8   ISM properties from JWST photometry of distant galaxies

Supervisor: Emma CURTIS LAKE (University of Hertforshire, UK)

Objectives:

1. To understand how JWST photometry can be used to constrain ISM properties of distant galaxies using the SED-fitting code, BEAGLE.
2. To understand the underlying modelling assumptions and how they affect the results.

Description: The James Webb Space Telescope Near-Infrared camera (NIRCam) allows for detailed analysis of galaxy physical properties across cosmic time thanks to the many broad, medium and narrow-band filters that can densely sample the spectral energy distributions (SEDs) of galaxies. In distant galaxies, the increasing equivalent width of nebular emission lines (thanks to evolution in the galaxies themselves, as well as decreasing observed flux density in the continuum) means that they can have a large impact on NIRCam fluxes for high-redshift galaxies (when present). This allows constraints to be placed on the ionised gas properties in these galaxies as well as the stellar properties. If time allows we can extend the analysis to NIRSpec PRISM spectra over the same field.

Docker should be installed prior to the school, and information for downloading the beagle docker image and stellar+nebular templates will be shared prior to the school. We will also use python (specifically `pyp-beagle` and `jupyter` notebooks).

We will analyse data from the JADES (JWST Advanced Deep Extragalactic Survey)[1] 3rd data release (specifics on what to download to follow) https://archive.stsci.edu/hlsp/jades.

[1]JADES - MAST The JWST Advanced Deep Survey (JADES) is the largest deep survey program that will be executed in the first few of years of operation of JWST. Three GTO Teams (NIRCam, NIRSpec, MIRI-U.S.) have combined time to produce a survey which will ultimately cover over 100 square arc minutes from 0.7 to 5 microns and 10 square arc minutes at 7.7 microns and produce thousands of galaxy spectra.

Project 9 Numerical simulations using the RAMSES and the AREPO codes

Supervisors: Simon GLOVER (University of Heidelberg, Germany) & Evangelia NTORMOUSI (SNS Pisa, Italy)

Objectives:

1. Learn to use an MHD code with simple initial conditions.
2. Perform analysis of the results and compare to analytical models.
3. Analyze complex, multi-component numerical simulations of galaxies.

Description: In this exercise we will learn how to use an MHD code to run numerical simulations and perform a preliminary analysis of the results. We will first test the different hydrodynamic solvers to see their effect on a simple solution, and then proceed to study two simple applications often encountered in the interstellar medium: a spherical shock and the Kelvin-Helmholtz instability.

1. First, you will have to download and install the code on your laptop or a server you can access remotely. Ideally, this should be done before arrival at the school. Detailed instructions and assistance will be provided.
2. The first exercise will be a simple wave advection, computed with different solvers. We will plot and compare the solutions to decide which solver we prefer for our problem.
3. The second exercise will be a Sedov blast wave in three dimensions. Once we calculate the numerical solution, we will compare it to the analytical one.
4. Finally, we will try slightly more complex initial conditions by simulating the Kelvin-Helmholtz instability in two or three dimensions, and observe its evolution over time.
5. In the second part of the session, we will provide snapshots from a complex, multi-component numerical simulation performed with the AREPO code. You will read in and analyze the results and infer properties of the simulated galaxy's ISM.

We will use python for post-processing the simulations. Details on how to install specific packages will also be provided before your arrival at the school.

Project 10 How to interpret molecular lines from dense gas in Galaxies

Supervisors: Serena VITI & Yuze ZHANG (University of Leiden, Netherlands)

Objectives:

1. Learn how to derive physical parameters from extragalactic molecular emission lines.
2. Learn how to use a chemical model with simple initial conditions.

Description: In this exercise we will learn how to derive the physical information from two locations in a nearby galaxy (the composite galaxy NGC 1068) by the use of two transitions of the CO molecule. In particular we shall test and look at the pros and cons of various tools such as LTE extrapolations (*e.g.* rotational diagrams), and non-LTE modelling. Once we derive as much as we can from the observed transitions we shall then use a chemical model (https://uclchem.github.io/) to help us interpret these results and derive a physical and temporal picture of the gas in these two locations.

GUIDELINES TO THE STUDENTS

1 Goals

Making people work together on a given project is usually very fruitful. The goals are the following.

- To teach you a particular set of skills related to the summer school's scientific themes.
  - You could pick a project that you are interested in, because it is relevant to your current work.
  - You could alternatively pick a project far from your current field, as a refreshing experience.
- By inciting you to work together, we hope to create links between students, and potentially with the advisers. It is also possible that some of these hands-on sessions will kick-start projects or collaborations.

2 Working on the Project

- The first session will likely be devoted to introducing everyone, and adapting the project more precisely to the skills and interests of the group.
- Meeting with the advisors is only a part of the session. You are then supposed to work by yourselves. There are no particular rules. You invest the amount of time you can in these projects.
- The projects have been designed so that they can be conducted on a personal laptop.
- Each team is self-organized. You decide how to split the tasks, and how to efficiently work together.

3 Presentation

Each team will present their achievements to the audience, on the last school day (Thursday, July 31st, from 4:15pm to 5:55pm).

- The order of the presentations will follow the project numbers in this document.
- Each team will have 10 minutes in total (including questions). You must therefore prepare a $\simeq 8$ minute talk maximum.
- Different team members can take turns to present different slides.