Molecular Gas Conditions and Star Formation in Nearby Galaxies

Project description:

Cold clouds of molecular gas of molecular gas are the sites of star formation. The conditions (temperature, density, turbulence, etc.) in these clouds determine the efficiency with which gas can be converted into stars, and at the same time star formation alters the conditions of the clouds through feedback.

In this project, we will use millimeter and sub-millimeter spectroscopic data – obtained with the Submillimeter Telescope, Kitt Peak 12m Telescope, Large Millimeter Telescope, and IRAM 30m Telescope – to measure gas conditions in a sample of 50 star forming galaxies. With this dataset, we will explore how the gas properties of galaxies interact with star formation rates, the presence of starburst events, and the shutting down of star formation to form quiescent galaxies.

A student working on this project will learn how to reduce millimeter-wave radio data, how to model and interpret spectral lines detected in this wavelength regime, and how measure the molecular gas properties of star forming galaxies. Depending on timing of the internship, there may also be opportunities to help design and (remotely) carry out observations with the Submillimeter Telescope in Arizona.

Desired skills:

A basic knowledge of programming in Python will be helpful.

Example reading materials

A. K. Leroy, E. Rosolowsky, A. Usero, et al. 2022, "Low-J CO Line Ratios from Single-dish CO Mapping Surveys and PHANGS-ALMA," *The Astrophysical Journal*, 927(2):149, arXiv:2109.11583

Finding Hidden Monsters

Project description:

Explore the fascinating realm of Active Galactic Nuclei (AGNs), dynamic cosmic entities fueled by the accretion onto supermassive black holes (SMBHs) nestled at the heart of galaxies. AGNs stand as the most luminous sustained phenomena in our universe, playing a pivotal role in the evolution of galaxies. However, unraveling the cosmic growth of SMBHs proves challenging due to the presence of nuclear- or galactic-scale obscuration, complicating the systematic identification of AGNs.

This summer project delves into the analysis of candidate obscured AGNs, strategically identified through cutting-edge machine-learning analyses. Optical spectroscopy data for these galaxies has been meticulously collected using 2- and 6-meter class ground-based observatories and subsequently reduced. Leveraging the power of Python programming, the student will embark on the intricate task of scrutinizing the optical spectroscopy of galaxies believed to harbor obscured SMBH activity.

Throughout the project, the student will gain proficiency in extracting crucial insights from the data, including the measurement of emission line properties and continuum features. This analysis will ultimately unveil the presence of AGN activity within these galaxies. The culmination of the project will not only witness the student successfully identifying AGNs but also characterizing additional features such as outflow strengths and properties. This comprehensive understanding will enable the placement of these systems within the broader context of obscured SMBH growth and its contribution to galaxy-SMBH co-evolution.

Desired skills:

Basic python knowledge would be highly desirable. Bonus skills would be familiarity with any or all of the following:

- FITS file format.
- The (UNIX) command line.
- Optical spectroscopy experience.
- Astronomy Python software (e.g. astropy).

Example reading materials

Spectroscopic identification of type 2 quasars at $z < 1$ in SDSS-III/BOSS by Yuan et al. (2015) provides a quick introduction to the field, outstanding problems, and examples of the kind of analyses that will be undertaken by the student.

Turbulence in protoplanetary disks produced by hydrodynamical instabilities

Project description:
Understanding the origin of turbulence in gas disks around newly-formed stars is crucial for a comprehensive understanding of planet formation, as this phenomenon significantly affects the transport, coagulation, and fragmentation of dust grains, thereby regulating their growth into bodies ranging from meters to eventually kilometers in size. In weakly ionized regions of protoplanetary disks, turbulence is likely controlled by hydrodynamical instabilities. Among these, the vertical shear instability (VSI) stands out as a rather robust mechanism due to its few requirements to operate, namely nonzero temperature gradients and short thermal relaxation timescales. While hydrodynamical models of turbulence typically assume vertically uniform temperature distributions, we know that the balance of stellar heating and infrared cooling induces a vertical temperature stratification, with higher temperatures close to the starlight-heated disk upper regions than at the disk midplane. This project aims to examine how the VSI behaves in hydrodynamical simulations of protoplanetary disks with realistic temperature distributions, which we can compute via Monte Carlo simulations of stellar irradiation. The goal is to explore how such a temperature stratification affects the transport of angular momentum, the development of long-standing structures like vortices, and the different regions of stability in realistic disk models.

The student undertaking this project will gain experience in hydrodynamical simulations conducted on high-performance computing clusters. On the scientific side, they will learn about the physics of accretion disks, planet formation, and radiative transfer. Potentially, emphasis can be made on the modeling of radiative transfer via Monte Carlo simulations.

Desired skills:
Knowledge of any programming language. Ideally knowledge of python and some basic knowledge of C.

Example reading materials
Radiation Hydrodynamical Turbulence in Protoplanetary Disks: Numerical Models and Observational Constraints, M. Flock et al. 2017, ApJ, 850, 131
https://iopscience.iop.org/article/10.3847/1538-4357/aa943f/pdf

Time-series analysis to probe the interior of massive stars

Project description:
Stars oscillate in much the same way as musical instruments, but at several closely-spaced frequencies. By observing stars over time, one can study these oscillations and probe the deep stellar interiors. Analyses of stellar time-series data usually occur in the Fourier (frequency) domain by computing the standard Lomb-Scargle (LS) periodogram, an estimator of the *power spectrum* underlying unevenly-sampled time-series data. However, the LS periodogram suffers from two statistical issues: inconsistency (or noise) and bias due to high spectral leakage. Patil et al. (2022) developed a new frequency analysis method called multitaper Non-Uniform Fast Fourier Transform (`mtNUFFT`) that helps resolve these two issues with the LS periodogram (refer also to Springford et al., 2020). They used the method to better characterise oscillations in red giant stars (also called pressure modes) as well as to automatically detect and estimate the periods of certain types of transiting exoplanets.
This work inspired the application of `mtNUFFT` to different types of oscillations such as gravity modes, which are oscillations observed in massive stars. The student will thus use `mtNUFFT` to perform gravity mode extraction in slowly pulsating B stars (SPB), and test whether it improves upon the state-of-the-art prewhitening method (Breger et al., 1993) adopted for these modes. The differences between literature estimates of mode frequencies are large for these massive stars, which makes it difficult to model their internal structure. This work will thus improve our understanding of the structure and evolution of massive stars.
The student will gain a good knowledge of time-domain astronomy and more specifically, the field of asteroseismology (study of stellar oscillations). They will also learn how to install, use, and potentially test Python packages used in astronomical data analysis.
The `mtNUFFT` frequency analysis method is implemented in the open-source Python package, `tapify`, that generally applies to time-domain astronomy. The student will directly work with this package. If time permits and if the student is interested, the results will be compared with the `multitaper` R package, which is a well-tested code for multitaper power spectrum estimation of evenly-sampled time-series.

Desired skills:
Knowledge of python is necessary to work on this project. Basic understanding of time-series analysis is desired but not required.

Example reading materials
Recommended reading for better understanding of the project includes Springford et al. (2020) and/or Patil et al. (2022).

References

Springford, A., Eadie, G., & Thomson, D. 2020, AJ, 159, 205, doi:10.3847/1538-3881/ab7fa1

Patil, A., Eadie, G., Speagle, J., & Thomson, D. 2022, arXiv e-prints, doi:10.48550/arXiv.2209.15027

Breger, M., Stich, J., Garrido, R., et al. 1993, A&A, 271, 482

Probing the 3D Nature of Exoplanet Atmospheres with JWST Data

Project description:
JWST is delivering incredibly precise measurements of exoplanet atmospheres and as such we are now able to extract information about the three-dimensional nature of exoplanets from transit light curves. Transit light curves are made by observing the flux of a star when a planet travels across its disk from our point of view. The subsequent decrease in the observed brightness due to the planet contains information about the atmosphere of the exoplanet itself. Studying the transit depth as a function of wavelength allows us to constrain the presence of atomic and molecular species in an exoplanet's atmosphere due to spectral imprints these absorbers leave on the transit depth. In the case of large temperature differences between the day and night sides of an exoplanet's atmosphere — as it is known for hot gas giants orbiting their host stars in close-in orbits — we can observe small asymmetries in the transit light curves due to the heat transport. In this project you will analyse precise JWST light curves of an exoplanet transit in multiple wavelength ranges and probe for these asymmetries. You will determine whether the exoplanet's temperature differences on day and night sides affect measurements of the planet's composition at the border between the day and night sides of the planet.
You will learn about exoplanet atmospheres and what we can measure by observing their spectra. You will use python packages to analyse JWST transit light curves and to measure the transit depth of an exoplanet at different wavelength ranges. Finally, you will learn to interpret your results and put it into the context of what we already know about the exoplanet WASP-121b.

Desired skills:
Knowledge of Python (e.g. using numpy, reading in files, data visualisation with matplotlib)
Understanding of data analysis and fitting methods

Example reading materials
N. Espinoza & K. Jones (2021), *Constraining Mornings and Evenings on Distant Worlds: A new Semianalytical Approach and Prospects with Transmission Spectroscopy*, The Astronomical Journal, Volume 162, Issue 4, id.165, 21 pp.

Searching for Hidden Black Holes

Project description:
Binary systems containing a black hole and a main sequence star are known to exist, but are difficult because they have very few observational signatures – although thousands are predicted to be hidden among observable stars, only 2 such binary systems are known. One method to search for these missing black holes is to identify stars whose shapes are gravitationally distorted by a nearby high-mass object ("ellipsoidal binaries"). We have identified a sample of ≈ 200 candidate black hole binaries, where the main sequence star is distorted in a way that suggests the companion is high-enough mass to be a black hole. However, because black holes are relatively rare, most (or perhaps all) of these are likely to be false positives (these may have companions who are lower-mass stars or other compact objects like white dwarfs). In this project, we will use spectra of the candidates to measure the radial velocities of the visible star in each, which we will then use to measure the masses of the unseen objects and confirm whether they are or are not black holes. If a black hole is found, that is a ground-breaking result! If we do not find any black holes, we will instead do some statistics to determine an upper limit on how common black holes can be.

This project will introduce you to a number of common astronomical techniques: we will handle optical spectra of a star, experience spectroscopic template cross-correlation to measure the radial velocity of a star, and then use model-fitting processes (in particular, an MCMC method) to fit to the measured radial velocities. Towards the end of the project, if time, we will work together on forward-modelling a simple black hole population model through a selection function to match the observed population density.

Desired skills:
Knowledge of Python.

Example reading materials
A relevant paper is Mazeh et al 2022: this paper is about a neutron star rather than a black hole, but the techniques they use are similar to what we will do.

The paper is here: https://arxiv.org/pdf/2206.11270.pdf

Determining strategies for efficient follow-up observations of candidates to massive stars with black hole companions

Project description:

The recent surge in gravitational wave detections has revolutionised astronomy, providing insights into collisions and mergers of dense objects like neutron star and black hole binaries. Massive stars, known for their high multiplicity fraction, are the progenitors of these intriguing objects. Our focus is on OB+BH binaries, an intermediate stage in the evolution towards binary compact systems, that provide crucial information on their formation and massive stars evolution.

SDSS-V will observe hundreds of thousands of massive stars for at least 3 epochs, utilising radial velocity measurements to identify binary stars. The selected candidates, possibly having black hole companions, will be further observed with high-resolution spectroscopy to determine their orbital properties. Given the numerous expected candidates, efficient follow-up strategies are imperative.

In this summer project, students will create an artificial sample of binary stars from observed distributions of orbital parameters and run simulations to determine the minimum number of observations required for an accurate orbital solution. The results obtained will be applied to an observational proposal for the FEROS spectrograph at ESO's La Silla Observatory in Chile.

Students will gain skills in using observed distributions for population synthesis studies, working with radial velocity measurements, determine orbital solutions, and writing observational proposals for follow-up studies.

Desired skills:
Experience with Python would be beneficial, but it is not a strict prerequisite, and students with a willingness to learn are also encouraged to apply.

Example reading materials
The SDSS-V sample: 2021A&A...650A.112Z
Predictions for OB+BH binaries: 2020A&A...638A..39L
Observed O+BH systems: 2022NatAs...6.1085S, 2022A&A...664A.159M

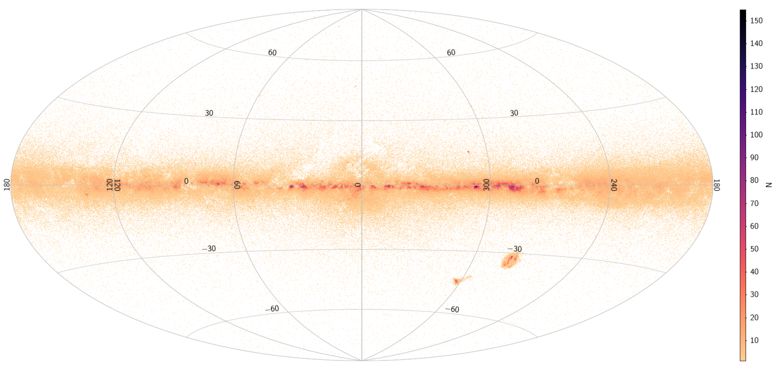

Figure 1: Distribution of the massive stars observed by SDSS-V, in Galactic coordinates, from Zari+2021.

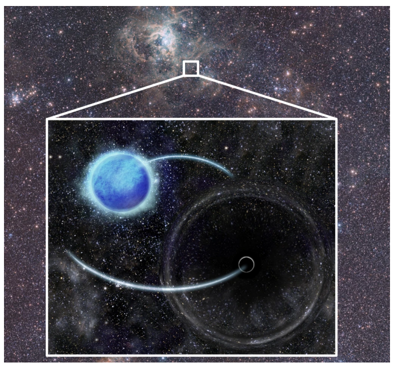

Figure 2: Artist impression of the O+BH binary VFTS 243 from Shenar+2022.

On the properties of Class 0/I protostellar cores in the Lambda Orionis molecular complex

Project description:

Stellar feedback (e.g. photoionization, stellar winds and supernova explosions) may shut star formation down or trigger new star formation in different Galactic environments. However, how the stellar feedback influences the new star formation is still unclear. We have observed eight Class 0/I protostellar cores located in the Planck cold clumps in Lambda Orionis complex in order to study the influence of stellar feedback on new star formation with the ALMA 12-m array in band 3. We aim to: (1). Study their dust emissivity spectral indices; (2). Investigate whether the envelopes are still in collapse; (3). Study outflow properties (4). Study PDR-like chemistry. The proposed high-resolution (1 arcsec or 400 AU) observations will shed light on how the properties of dense cores and star formation therein are influenced by radiation feedback from HII regions.
With this project the student will learn how to image the radio interferometric data using the CASA, including continuum and lines images. The student is also expected to learn how to analysis the data using the python package (e.g., Anaconda, Astropy) and produce publication-ready images. Ultimately, we hope the student could try to publish a short paper bashed on this project, so the student will learn how to prepare a draft for the publication.

Desired skills:

It would be good to have some basic knowledge of python. Ideally, some experiences on CASA would be perfect, but not required.

Example reading materials

The student could take a look at this paper "The dangers of being trigger-happy; Dale, J. E., et al, MNRAS, 450, 1199-1211, 2015".

Mapping interstellar extinction with stellar clusters

Project description:

Context: Stellar clusters are groups of stars born together from the same molecular cloud, which means they all share the same age and chemical composition. In a colour-magnitude diagram (CMD), stars from the same cluster are expected to align along a thin sequence, whose shape is an indicator of cluster age. The presence of interstellar dust between us and the cluster causes the stars to appear redder and fainter. When we estimate cluster ages from CMDs we often assume that extinction is uniform across the field of view, but many clusters exhibit a broadened sequence (e.g. left panel in Fig. 1) showing that stars in certain regions of the cluster are more strongly affected by extinction.

Aims: 1) Identifying (e.g. through machine learning) clusters affected by inhomogeneous extinction and applying extinction corrections to improve age estimates. 2) Comparing the extinction obtained for clusters to existing 3D dust maps, to assess the accuracy of those maps and whether clusters can be used as anchors to improve extinction models.

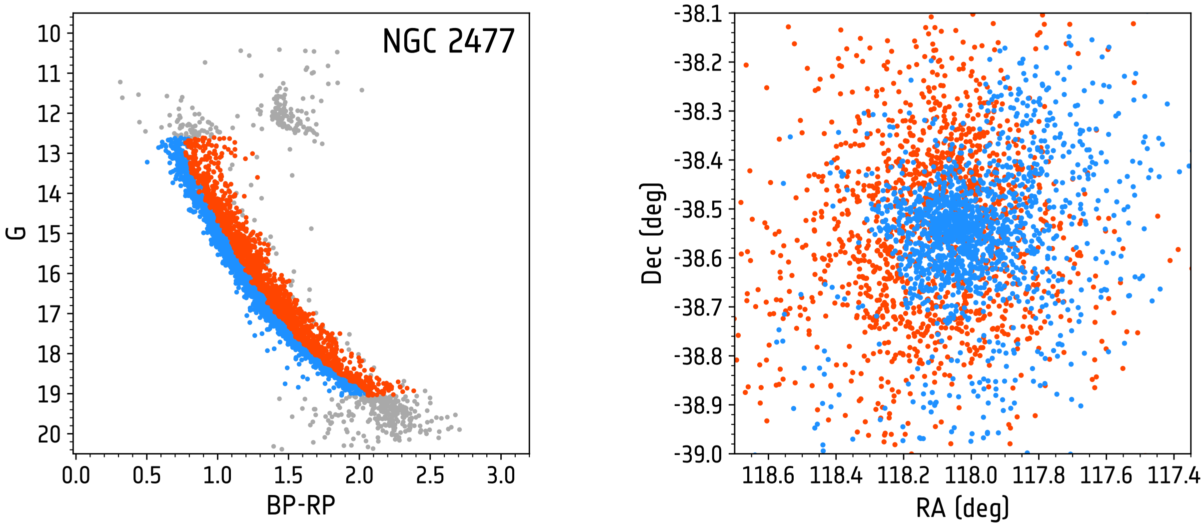

Figure 1: Left: CMD of NGC 2477, with its broad sequence roughly split into a blue and red edge. Right: distribution of those stars on the sky. The strong correlations between colour and sky position is due to inhomogeneous reddening, here mostly affecting the outskirts of the cluster.

This project relies on *Gaia* data, which is the deepest and most precise 3D catalogue of Milky Way stars ever made, with 1.8 billion objects. The student will learn to access and manipulate this large data set and to mine for particular objects, as well as visualising dust distribution, for instance from the models of Green et al. (2019ApJ...887...93G) and Dharmawardena et al. (2023MNRAS.519..228D) developed at MPIA. The student will also learn how to apply extinction corrections depending on stellar types (possibly using *Gaia* XP spectra), and how to estimate ages with theoretical isochrones.

Desired skills:

At least some basic knowledge of Python is desirable by the start of the project.

Example reading materials

More context about *Gaia* and star clusters: *"Painting a portrait of the Galactic disc with its stellar clusters"* Cantat-Gaudin et al. (2020A&A...640A...1C)

Exploring the fields of z∼6 radio-loud AGN with multi-wavelength datasets

Project description:
Radio-loud active galactic nuclei (AGN) are growing supermassive black holes (SMBHs) that are able to expel part of the accreting matter into two relativistic bipolar jets. Understanding the mechanisms responsible for the launch and the emission of these jets is of crucial importance for studying their role in SMBH accretion and evolution and for investigating their feedback on the host-galaxies and surrounding environments. Radio AGN at cosmic dawn (when the Universe was ≤1 Gyr old, $z \geq 6$) are indispensable tools for studying the early evolutionary stage of the first jetted SMBHs, their feedback on the host galaxy and the environment, and their contribution to the re-ionization epoch. Therefore, a detailed study of these objects is necessary to better constrain the properties of jetted SMBHs in the first gigayears following the Big Bang.
In this project, the student will explore the large scale field (∼Mpc^2) of z> 6 radio-loud AGN to characterise their environment. The student will exploit deep, dedicated multi-wavelength optical photometric catalogs (g, r, i, z, Y bands) together with available radio and X-ray datasets to identify and classify sources all over the field.
The student will learn how to deal with large and multi-wavelength datasets and how to classify different type of objects, like quasars, galaxies, stars through, for example, the color-color technique.

Desired skills:
Knowledge of python, matplotlib or another plotting tool.
Knowledge of TOPCAT or Sextractor or experience with photometry would be an asset but not a requirement.

Example reading materials
Section 5.5 of Fan, Banados and Simcoe review (https://arxiv.org/pdf/2212.06907.pdf). In that section several useful papers are mentioned; the student might would read at least the following paper:
Morselli L., Mignoli M., Gilli R., et al., 2014, A&A, 568, A1
(https://www.aanda.org/articles/aa/pdf/2014/08/aa23853-14.pdf).

Do Active Galactic Nuclei coexist with extreme starbursts in massive galaxies in the distant Universe?

Project description:

Roughly half of all star formation in the Universe is obscured by dust, as traced by sub/millimetre emission. Studying this obscured activity is crucial for advancing our understanding of galaxy formation and growth, as recent studies suggest that nearly all massive galaxies ($M* \gtrsim 10^{11}$ $M\odot$) in the distant Universe have experienced such a sub-millimetre-luminous phase. These extreme galaxies are among the most actively star-forming systems, with inferred star-formation rates up to 1000 times higher than in our Milky Way. Such intense star formation may be triggered by the merging of two massive galaxies, as suggested by studies of local galaxies. In this evolutionary scenario, their supermassive black holes merge during final coalescence, forming an active galactic nucleus (AGN) that quenches star formation. The resulting galaxy shines briefly as an obscured or unobscured AGN (or quasar), eventually evolving into a massive elliptical galaxy. However, at high redshift, such extremely star-forming galaxies are ∼100 times more ubiquitous, more luminous, and show a range of morphologies, complicating this simple scenario. Hence, the questions remain: What powers the infrared luminosity of these high redshift dust-obscured galaxies? Are they powered by the same mechanisms (starbursts and/or AGN) as their local counterparts? How reliably can we infer the AGN contribution in such systems, and can AGN possibly dominate their dust emission?

In this project, the student will analyze the largest publicly available sample of sub-millimetre-selected galaxies to infer the contribution of AGN to dust emission and its impact on our understanding of the physical properties of this important high-redshift population. The student will learn to interpret photometric data from some of the most powerful telescopes (e.g., HST, ALMA) through spectral energy distribution fitting techniques. Using existing software the student will fit stellar and AGN components to the observed spectral energy distribution to infer key physical properties of these extreme starburst galaxies (e.g., stellar mass, star formation rate, dust mass, AGN luminosity).

Desired skills:

Knowledge of python is highly desirable. Some previous experience in data analysis would be preferable.

Example reading materials

Reviews of dusty star-forming galaxies:
https://arxiv.org/abs/1402.1456;
https://arxiv.org/abs/2004.00934

Jellyfish galaxies as probe of galaxy evolution and cosmic gas

Project description:

Jellyfish are satellite galaxies with manifest signatures of ram pressure stripping, in particular exhibiting one or more "tail" of gas that stem from the main body of the galaxy and stretch in one preferred direction. The particular morphological features of jellyfish arise because such galaxies interact with a surrounding gaseous medium as the one that permeates galaxy groups and clusters.

In my team, we have been studying jellyfish galaxies by using the results of the IllustrisTNG simulations: https://www.tng-project.org/. We have even engaged the public with a so-called Zooniverse project (https://www.zooniverse.org/projects/apillepich/cosmological-jellyfish), aimed at identifying jellyfish galaxies among thousands of gas maps of simulated systems.

For a summer internship, I propose an analysis project based on the IllustrisTNG cosmological simulations and focused on such class of objects. Depending on the preference of the student, a summer project in my team could be related to ideas like the following:

- Can we construct a machine-learning algorithm that replicates the visual inspection of galaxies for the identification of jellyfish galaxies in other simulated and observed galaxy samples?
- What are the properties of the magnetic fields in the body, tail, and surrounding medium of jellyfish galaxies?
- The detectability of jellyfish galaxies, and the length of their ram pressure-stripped tails, across wavelengths and gas phases.
- How long does the jellyfish phase last in satellite galaxies?
- Do all satellite galaxies undergo a jellyfish phase?

Technically, the completion of the summer project would allow a student to become effective and efficient in coding e.g. in Python, also remotely at our supercomputers, to become familiar and proficient in analysing large and complex datasets, to learn how to make sense of the many physical phenomena that we think determine galaxy evolution, and to become familiar with the numerical and physics foundation of cosmological simulations for galaxy physics.

Desired skills:

Some knowledge in coding scripts e.g. with Python.
Some familiarity with working via Terminal.

Example reading materials

https://ui.adsabs.harvard.edu/abs/2019MNRAS.483.1042Y/abstract
https://ui.adsabs.harvard.edu/abs/2023MNRAS.tmp.3553Z/abstract
https://www.tng-project.org

Understanding the formation and evolution of Milky Way and Andromeda-like galaxies with the TNG50 simulation

Project description:

In my team, over the past few years we have been focusing in extracting useful scientific results from the IllustrisTNG simulations: https://www.tng-project.org/, with a focus on the formation and evolution of galaxies in the cosmological context.

For a summer internship, I propose an analysis project based on the TNG50 cosmological simulation, which samples hundreds of massive galaxies (like our own Milky Way and above) while simultaneously resolving details of their internal structures.

Depending on the preference of the student, a summer project in my team could be related to ideas like the following, all focused on late-type galaxies similar to our Galaxy or Andromeda:

- What is the connection between stellar bars and "bars" in the gas phase?
- How do the physical and star-formation properties of the gas change within a galaxy body, i.e. across spiral arms, in the bar region or in the interarms?
- Are the physical and star-formation properties of the gas different between barred and non-barred galaxies?
- How do bars funnel gas towards the galaxy centres?
- Can we construct a machine-learning algorithm that replicates the visual inspection of galaxies for the identification of bars vs. Non-barred galaxies, e.g. with the Manga survey?
- How many disk stars MW/M31-like galaxies have been produced in-situ vs. accreted from satellites and mergers?
- Etc.

See https://www.tng-project.org/results/ for examples of scientific questions that can be addressed with our simulations.

Technically, the completion of the summer project would allow a student to become effective and efficient in coding e.g. in Python, also remotely at our supercomputers, to become familiar and proficient in analysing large and complex datasets, to learn how to make sense of the many physical phenomena that we think determine galaxy evolution, and to become familiar with the numerical and physics foundation of cosmological simulations for galaxy physics.

Desired skills:

Some knowledge in coding scripts e.g. with Python.
Some familiarity with working via Terminal.

Example reading materials
https://ui.adsabs.harvard.edu/abs/2023arXiv230316217P/abstract
https://www.tng-project.org

Keeping adaptive optics systems well-aligned during closed-loop operation

Project description:

The real-time control system for the adaptive optics (AO) correction for the METIS instrument at the ELT is under active development at MPIA. Besides the main control loop that generates correction signals from wavefront sensor (WFS) data and uses these to steer the adaptive optical elements in the telescope infrastructure in real-time, there are several auxiliary loops that monitor the state of the system and ensure that all components remain well in sync with each other. One of these loops will execute the task of tracking the relative alignment - or *registration* - between the high-order deformable mirror (DM), which is part of the telescope, and the wavefront sensor, which is inside the instrument that sits on the Nasmyth platform. The fundamental concept is to command the DM to form dedicated patterns, and to read back the WFS response to determine the relative shift, rotation, and scale between those two components. A suitable procedure for achieving this is described in a research paper and available as a prototype implementation. The task is to first transfer this prototype onto the already existing METIS simulation environment, perform tests in simulation, and eventually deploy the code in the actual soft real-time computer (SRTC) system.

The METIS simulation environment is set up in COMPASS, which is a GPU-based simulation system for AO systems that features a python layer for scripting, and for higher-layer component simulations. Currently under development is the SRCT system, which happens mostly in python. We have a large team working on this development, of which the student should temporarily form a part. The development of the code base is done on a git repository. The project offers the interesting opportunity to work at the interface between science, engineering, and software development.

Desired skills:

The candidate should have a profound command of python, ideally in the context numpy array operations. In addition, a good knowledge of wave and fourier optics will clearly be an asset.

Example reading materials

Simulating METIS' SCAO System - M. Feldt, H. Steuer, C. Correia, A. Obereder, S. Raffetseder, J. Shatokina, F. Cantalloube - 2023, AO4ELT7, http://arxiv.org/abs/2311.13437