Astronomy & Physical Cosmology
speciality of the official
Master in Theoretical Physics

Offers
for

MSc Theses
2024/25

On the following pages the possible projects for a MSc thesis are listed. Please note that the MSc thesis is not restricted to be selected from this list; this list simply reflects research interests within the Department and its associated members. You always have the option to talk to the members and come up with a new project.

Note that each project has to be a work worth 12 ECTS which translates to 300 hours (ca. 8 weeks) of work. The work will primarily be undertaken during (and after) the third trimester, but you are free to start as early as possible.

There will be two calls to present the master thesis: one in end-June/early July and another one in early-September.

The list provided here is ordered by the surnames of the supervisor.

Javier Álvarez Marquez (CAB) and Luis Colina (CAB), Daniel Ceverino (UAM)

Galaxies at redshifts beyond z > 6

The nature of the sources that reionize the universe is still unknown. Imaging surveys have concluded that galaxies are detected as increasingly strong [OIII]-line emitters at high redshifts. Recent studies argue that extreme [OIII] emitters (EW[OIII]5007Å>1000Å) at redshifts above 6 should be common, and be responsible for the reionization of the universe (so called Epoch of Reionization, EoR). However, their physical properties, especially Lyman continuum emissivity, are not firmly established yet. The group at CAB has recently been awarded a medium-size program with the James Webb Space Telescope (JWST) to investigate a complete sample of galaxies (LAEs/LBGs) at redshifts above 6, and identified as [OIII]88um emitters with ALMA. These data will establish i) the age and mass of the stellar population, ii) the structure of the stellar population and ionized gas nebula, iii) the physical conditions, kinematics and ionization status of the ISM, and iv) the LyC escape fraction. The combination of JWST's deep, high-angular resolution multiwavelength imaging and spectroscopy, and ancillary ALMA data, will provide key information on the early stellar mass and galaxy assembly during the yet unexplored Epoch of Reionization.

The potential candidate will work with the PI (Javier Álvarez), and coI (Luis Colina) of the JWST proposal to establish the age and stellar mass of the sample galaxies based on simulated spectral templates and the combination of existing data (James Webb Space Telescope, ALMA). *The potential candidate could extend these studies beyond the MSc thesis into a PhD project, depending upon final qualifications and available funding*.

A good knowledge of English at all levels is required, as well as knowledge of programming in python.

Daniel de Andres (UAM), Weiguang Cui (UAM), & Gustavo Yepes (UAM)

AI-mapping of initial conditions of the Universe

Reproducing the observed Universe is a huge project with many benefits. However, it is not easy to make accurate simulations to precisely mimic the Universe we see, see the CLUES project for example. One of the difficulties lies in the so-called constrained initial conditions, with which the simulations start and finally can output the analogue of the observed Universe, for example, SDSS survey.

The evolution of The Universe is determined by its initial conditions and the laws of physics. These simulations compute the gravitational evolution of N-body particles given a set of typically Gaussian initial conditions representing the early universe, a process that is computationally costly. Deep learning methods have recently been used for accelerating the forward mapping, i.e. from a linear regime (initial conditions) to the non-linear small structures at redshift z=0. However, the inverse problem is more challenging. In this context, this master thesis project aims at using state-of-the-art Machine Learning (ML) techniques to train ML models that can map the simulation output at z=0 to their initial conditions at high redshift.

The master student is expected to learn the state-of-the-art of Cosmological Simulations and Artificial Intelligence. He/she will work with the computational cosmology group at UAM, which is part of different international collaborations such as The Three Hundred and CLUES simulation projects.

Software that will be used: Python, Tensorflow, Pytorch.

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Daniel de Andrés (UAM) and Gustavo Yepes (UAM)

Generative AI for simulations of galaxy clusters.

To study galaxy clusters, gravity and baryonic physics need to be taken into consideration. Cosmological simulations of galaxy clusters including hydrodynamics are very costly and thus, only a limited number of objects is re-simulated with full baryonic physics. The Three Hundred Project (The300, http://The300-project.org) aims at re-simulating 324 galaxy clusters and their environment. This set of simulations includes different baryonic physics models, making it the perfect environment for studying the connection between baryons and dark matter, filamentary structure, gravitational lensing, etc.

Deep generative models have recently emerged as new tools for addressing the issue of the computational time required for running these large simulations. Models such as Generative Adversarial Networks and Diffusion models have proven to be very useful for generating images in computer vision problems. The aim of this project is to explore the state-of-the-art generative models and assess their fidelity in simulating observations of clusters of galaxies. The300 cosmological hydrodynamical simulations will be considered as the optimal training database.

The master student is expected to learn the state-of-the-art of Cosmological Simulations and Artificial Intelligence. He/she will be working within the computational cosmology group at UAM, part of different international collaborations such as The Three Hundred and CLUES simulation projects.

Software that will be used: Python, Tensorflow, Pytorch.

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Yago Ascasibar (UAM)

Computational multi-messenger astronomy

In recent years, multi-messenger astronomy has emerged as a powerful tool for exploring the universe. By combining observations at different wavelengths, as well as other tracers (in our case, cosmic rays), we aim to gain a more comprehensive understanding of astronomical phenomena. This TFM involves the development of new tools to analyse multi-messenger data and/or use them to shed some light on unsolved problems. Depending on their interests, students may focus on one or more of the following projects:

a) One source finder to rule them all: The first step in the analysis of any astronomical object is its detection. In this project, the students will learn about different algorithms that apply in different contexts, measure their performance, and help develop and test a new scheme that works in a wide variety of situations (emission/absorption, 1/2/3D, optical/radio) with a minimum number of free parameters.

b) Aperture photometry in AstroBrowser: In this project, students will access public databases of astronomical images and compute the flux received at different wavelengths for different galaxy samples. For resolved systems, they will also derive surface brightness profiles in elliptical rings. Then, they may consider the implementation of their recipes into https://astrobrowser.ft.uam.es and/or turn their attention to further scientific analysis (e.g. project c).

c) The star formation history of galaxies: There is a lot of information encoded in the multi-wavelength spectral energy distribution of a luminous object. For galaxies, one of the main variables is the star formation history, i.e. how many stars are born as a function of time since the beginning of the universe up to the present day. Here, the students will learn the basics of Bayesian inference and put it to practice in this particular inverse problem.

d) Dark matter and cosmic rays: Cosmic rays are relativistic particles that propagate through the interstellar and intergalactic medium. The origin of positrons, both at the central regions of the Milky Way and the Solar neighbourhood, is still a mystery. The favoured candidates are supernova remnants, pulsars, and potentially the annihilation or decay of dark matter particles. After being introduced to the fundamentals of astroparticle physics, the students will use the code DRAGON to model the production and propagation of cosmic rays throughout the Galaxy, trying to constrain their main sources and propagation parameters.

You are more than welcome to contact me (yago.ascasibar at uam.es) for further information.

Yago Ascasibar (UAM)

Extragalactic astrophysics and cosmology

In this TFM, students will investigate the universe beyond our Milky Way, addressing different open issues related to the formation and chemical evolution of galaxies within a cosmological context. Depending on their interests, they may focus on one or more of the following projects:

a) A self-consistent model of spiral galaxies: The student will combine high-resolution optical and radio observations for a sample of galaxies of different mass, star formation activity, environment, and dynamical state. This will make it possible to characterise scaling relations with an unprecedented level of detail, including relevant variables such as e.g. the kinematics and chemical composition of the stars and ionised gas, inferred from optical data, and the kinematics of the cold gas detected in radio, tracing turbulent motions and the gravitational potential of the dark matter halo.

b) Galaxies as cosmic probes: The student will first learn about the main tracers of the composition and expansion history of the universe: the Cosmic Microwave Background (CMB) radiation, the scale of the Baryon Acoustic Oscillations (BAO), and the Hubble-Lemaître diagram of Type Ia supernovae and other standard candles. As the precision of these tracers has improved beyond a few per cent, several tensions have emerged between the low- and high-redshift probes, and the goal of this project is to calibrate independent tracers of the cosmic expansion based on the statistics of the galaxy population.

c) Assessing the viability of a finite universe: If all the cosmic probes (CMB, BAO, SNe, cosmic chronometers) turned out to be correctly calibrated, their results would imply that the ΛCDM model may not be the ultimate description of our universe. Here we will consider a spatially finite model where three-dimensional space is a hypersphere of radius R(t) and test its compatibility with the latest measurements.

You are more than welcome to contact me (yago.ascasibar at uam.es) for further information.

Ricardo Carrera (INAF) & Nataly Ospina (UAM)

Structural parameters of Open Clusters

Open clusters (OCs) are groups from several hundreds to tens of thousands of gravitationally bound stars located in the Galactic disc. Unlike more massive and complex globular clusters all the stars of a given OC seem to share the same properties such as age, kinematics and initial chemical composition. Open clusters cover a wide range of masses, luminosities, structural characteristics and ages. All together has motivated their use as probes of a large variety of astrophysical phenomena. They have been key laboratories to understand the stellar interiors, nucleosynthesis and evolution in issues such as convection and radiation transport.

During their lives, open clusters are strongly affected by stellar evolution, internal dynamics and external forces. Very young clusters suffer infant mortality. Protostellar outflows, photoionization, radiation pressure, or supernova shocks expel high speed gas that is able to evaporate the less concentrated systems. The dynamical evolution of surviving gas-free clusters is driven by relaxation. The stars randomly exchange energy via gravitational interactions, causing equipartition of energy between stars of different masses. This causes a mass segregated system with the most massive objects concentrated in the centre while the lower mass stars migrate to the outskirts, forming a halo. Some of these stars acquire enough velocity to escape from the system, resulting in its gradual evaporation. This dissolution is amplified by the forces acting on these systems as they orbit in the Galaxy, such as encounters with giant molecular clouds or passes through the disc. Therefore, according to dynamical simulations a typical cluster will evaporate in a timescale of ~1 Ga. However, between 8 and 10 % of the more than 6,800 known and candidate open clusters have ages older than 1 Ga. The properties of this older population are related to the dynamical evolution of clusters and the balance between mechanisms of cluster formation and dissolution.

Making use of the Gaia satellite data, the student will investigate the spatial distribution and structural parameters of a sample of open clusters with ages around 1 Ga in order to constrain their dynamical evolution, and longevity. During the development of the work, the student will acquire experience in the analysis of large data samples together with programming skills in python.

References:

Alvarez-Baena et al. 2024, A&A in press, arXiv:2404.12523

Carrera et al. 2019 A&A, 627, A119, arXiv:1905.02020

Ricardo Carrera (INAF) & Nataly Ospina (UAM)

Open Clusters kinematics

Discs are the defining stellar component of most late-type galaxies, including the Milky Way. They contain a substantial fraction of the baryonic matter, angular momentum and evolutionary activity of these galaxies, such as formation of stars, spiral arms or bars, and the various forms of secular evolution. Understanding the formation and evolution of discs is, therefore, one of the key goals of galaxy formation research. The disc evolution is fossilized in the orbital distribution of stars, their chemical composition and ages as a function of position. The disc of our own galaxy, the Milky Way, offers an excellent test bed for investigating its evolutionIn through resolving their stellar populations into individual stars. However, part of this information may be diluted through dynamical evolution and radial mixing in the disc, which is less severe for clusters than for field stars. Moreover, some of the OC properties, such as distances or ages, can be accurately determined.

Taken advantage of the radial velocities derived in the framework of the OCCASO (Open Clusters Chemical Abundances from Spanish Observatories) project, together with Gaia proper motions and parallaxes the project aims to investigate the kinematics of a sample of more than 70 open clusters, for instance if the follow the thin disc kinematics. Moreover, we will also integrate their orbits in order to investigate several aspects such as the radial migration.

References:

Carrera et al. 2022, A&A, 658, A14, arXiv:2110.02110
Casamiquela et al. 2016 MNRAS, 458, 3150, arXiv:1603.00659

Daniel Ceverino (UAM)

Protocúmulos de galaxias en el Universo primitivo

Los cúmulos de galaxias con cientos o miles de miembros constituyen los mayores objetos del Universo. Los astrofísicos se preguntan cómo se pudieron formar estos gigantes cuando el universo era joven.

Las simulaciones cosmológicas de formación de galaxias pueden ayudar a aclarar este misterio. Este trabajo utiliza la base de datos del proyecto “The Three Hundred” para identificar y caracterizar protocúmulos así como las galaxias que albergan.

El estudiante se familiarizara con algoritmos de “data mining” y tendrá que extraer información científicamente relevante para componer un modelo de formación y evolución de protocúmulos.

Mínimos requisitos: conocimientos de programación en python, C or Fortran.

Daniel Ceverino (UAM)

Synthetic images from cosmological simulations of first galaxies and the effect of dust attenuation

The new James Webb Space Telescope (JWST), the successor of the Hubble Space Telescope, is revolutionizing our understanding of the first galaxies that formed in the early Universe. This is one of the main objectives of this telescope (https://jwst.nasa.gov/content/science/firstLight.html).

The goal of this project is the understanding of the role of dust attenuation in synthetic images of first galaxies that can be compared directly with JWST observations. From a large set of existing images from the FirstLight database, the student will compare images with and without attenuation and study its effect in the galaxy morphology.

Tentative observations suggest that dust attenuation is less severe in small, faint galaxies and it increases in more massive galaxies with higher gas (and dust) column densities. Due to the large sample of galaxies with different masses, the student will be able to test different models of dust attenuation and address the importance of dust as a function of galaxy mass and redshift.

The student will use the FirstLight database, a large number of cosmological simulations of first galaxies (N-body + hydro). More information on the project website:
http://odin.ft.uam.es/FirstLight/index.html

Requirements: Good programming skills in any of the following languages: Fortran, C, Python

Daniel Ceverino (UAM)

The formation of globular clusters in giant clumps in the early Universe

Globular clusters are the oldest stellar systems in our galaxy. They must have formed in extreme conditions of densities and pressures in the early Universe. One of the formation theories suggests that giant clumps of gas in early galaxies may host such conditions. The goal of this project is to use a catalog of giant clumps extracted from cosmological simulations of galaxy formation, the VELA simulations (https://www.nirmandelker.com/the-vela-simulation-suite). The student will populate these clumps with globular clusters according to different formation scenarios.

Requirements: Good programming skills in any of the following languages: Fortran, C, Python

Laura Colzi (CAB)

Unveiling the origin of nitrogen fractionation

The study of isotopic ratios, like the 14N/15N and 12C/13C, of molecules towards star-forming regions in our Galaxy gives important information about the chemical history of the molecular cloud itself and of the entire Milky Way, including our Solar system. However, the chemical processes that cause the spread of 14N/15N values (N-fractionation) within the same molecular cloud are still not fully understood. Only recent chemical models proposed a dependence of the 14N/15N ratios on the UV field exposure of the molecular cloud, which however needs to be confirmed observationally.

In this thesis project the student will perform a direct test to the dependence of N-fractionation values with the UV field, measuring the 14N/15N ratio of HCN and HNC towards the Monoceros R2 photo-dominated region. In particular, we have recently obtained observations with the IRAM 30m radiotelescope in Pico Veleta (Granada, Spain) towards two regions, the ionization front exposed to a strong UV field, and a northern embedded region where photons could not arrive. These observations are decisive in testing the importance of UV field to local N-fractionation processes.

The student will learn how to use the astrophysical analysis software GILDAS and MADCUBA to analyse spectra in the millimeter wavelengths, will identify the rotational transitions of the molecules, and derive the molecular abundances and abundance ratios. Then, the student will compare the results with observations and chemical models in the literature and will discuss about the possible implications on local N-fractionation.

This work will be used for the preparation of a publication in an astrophysical journal.

This project will be conducted within the “Chemical complexity in the ISM and star formation” group of the Centro de Astrobiología (website: https://cab.inta-csic.es/astrochem/index.html).

For more information contact: lcolzi@cab.inta-csic.es

Weiguang Cui (UAM)

The difference between observed and simulated galaxies -- the effect of galaxy finder

Understanding the galaxies, i.e. their properties, requires identifying them in the first place from both observation and theory sides. However, galaxy finding in observation is driven by geometry methods, while simulated galaxies are normally identified based on their physical property – a gravity-bound object. Are they the same? Apparently not. The main purpose of this project is to quantify the differences between observational defined galaxy and theoretical defined galaxy. This can be only done in one way – analysing the simulated galaxy with observational methods, because getting the physical quantities, such as star velocity, of observed galaxies is very hard.

In this project, the student will work with the simulated galaxies from the 300 project. He/She will first identify the galaxy from mock images of galaxy cluster with PhotoUtil (https://github.com/astropy/photutils). Then, he/she will crossmatch these identified galaxies with the theoretical identified galaxies, study their property differences, and present the result statistically.

Prerequisite Knowledge and Skills:
python, knowledges of galaxy finding software (desired) and numerical simulation (desired)

References

The 300 project: Cui et al. 2018, https://doi.org/10.1093/mnras/sty2111
PhotoUtil: Bradley et al. 2019, https://doi.org/10.5281/zenodo.2533376

Angeles Diaz (UAM), Sandra Zamora (UAM)

Derivation of abundance gradients in the face-on spiral galaxy NGC 1058.
Implications for the formation and evolution of galactic discs.

The importance of the knowledge of abundance distributions in spiral galaxies is widely recognized as a probe of their chemical evolution and star formation histories. The observation and analysis of HII regions provide excellent means for deriving chemical abundances of different elements, both primordial and by-products of stellar nucleosynthesis. This information is central to guide theoretical models of the formation and evolution of galaxies. Among the different abundance related parameters employed in the study of spirals are: the radial metallicity gradient, the average metallicity at a given fiducial galactic radius, and the central metallicity value, where metallicity usually refers to oxygen abundance. In fact, the two latter parameters rely on the determination of the first, since they are determined either by interpolation and extrapolation respectively.

Chemical evolution models have shown that: (1) abundance ratios between elements depend mostly on stellar nucleosynthesis and the initial Mass Function (IMF); (2) the slope of any abundance gradient is not sensitive at all to the adopted nucleosynthesis; and (3) the predicted absolute abundance of any element depends on all adopted parameters and hence it does not represent by itself a good test of any theory although it should be reproduced by any self consistent model.

However, the determination of accurate abundance gradients is not an easy task. In nearby galaxies, abundances have been found to decrease with galactocentric distance and, since these abundances control the cooling of the ionised gas, different techniques implying direct, empirical or semi-empirical methods, are needed to derived abundances throughout galactic discs.
We have secured long slit spectrophotometric data along the disc of the face-on spiral galaxy NGC 1058 obtained with the ISIS spectrograph attached to the 4.2m WHT telescope in La Palma Observatory. The spectral range covers from 3500 to 10000 Å simultaneously. These observations will allow the determination of unambiguous elemental abundance gradients thus providing a clear picture of the true metallicity distribution in the galaxy, either giving support or rejecting the hypothesis of the multi- component abundance gradients for normal spiral galaxies, compared to the classic scenario of a well- behaved smooth linear negative logarithmic gradient throughout all galactocentric distances, with important implications for the formation and chemical evolution of these objects.

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Violeta González Pérez (UAM), Dante Paz (Universidad Nacional de Córdoba, Argentina) and Antonela Taverna (UNAM, México)

Cosmic rulers as a function of environment

The Baryon Acoustic Oscillations (BAO) are fluctuations in the density of matter. The BAO are cosmic rulers that have been extensively used to understand the composition of the Universe at different cosmic epochs. We can only use galaxies and gas as bias tracers of the underlying distribution of dark matter. With this project we want to understand if the BAO peak changes depending on the large scale structure environment of the visible matter.

For this purpose we will use the algorithms Vweb and Pweb (Cui et al. 2018) run on the UNIT N-body dark matter only simulation (Chuang et al. 2020) to measure the position and shape of the BAO for haloes living in different environments: voids, walls, filaments or knots. We will also explore how the BAO depends on the tidal anisotropy, a measurement of local environment (e.g. Ramakrishnan et al. 2019).

The first step of this project will be to explore the pipeline using dark matter haloes selected by their mass.

This project will require to code and to deal with large quantities of data in different formats ("data mining").

REFERENCES:

Chuang+2019: https://ui.adsabs.harvard.edu/abs/2019MNRAS.487...48C/abstract

Cui+2018: https://ui.adsabs.harvard.edu/abs/2018MNRAS.473...68C/abstract

Ramakrishnan+2019: https://ui.adsabs.harvard.edu/abs/2019MNRAS.489.2977R/abstract

Tomás Hough and Alejandro Jiménez (UAM) - 2024/2025

“Machine Learning Analysis of Satellite Galaxies in Unrelaxed Clusters”

Galaxies located in high-density environments are more likely to be quiescent, and to have redder colours and more spheroidal morphology than galaxies with similar stellar mass located in the field. Once a galaxy enters a high-density environment like a cluster, physical processes associated to the environment (such as ram-pressure stripping, tidal stripping and others) affect the gas content of the galaxy, hence altering its properties.

In particular, the gas content and star-formation rate of satellite galaxies depend not only on local density, but also the orbital characteristics of the satellite population. There can be defined four general galaxy populations around clusters: neighboring galaxies (located outside the cluster), recent infallers (galaxies that have entered the cluster a few Gyrs ago), ancient infallers (entered the cluster many Gyrs ago) and backsplash galaxies (have entered the cluster, and due to their orbital motion they are located outside the cluster).

In Hough et al. (2023, https://arxiv.org/pdf/2211.04485), the evolution of the properties of this population of galaxies were studied using the Three Hundred Cluster simulations along with the SAG semi-analytic model of galaxy formation and evolution, using only relaxed galaxy clusters.

It is expected that the environmental effects depend indirectly on the dynamical state of the cluster, hence altering the properties of galaxies in a different manner than in relaxed clusters. The proposal for the TFM is to extend the mentioned work, using now unrelaxed galaxy clusters.

To do all this, machine learning techniques will be used to identify the different galaxy populations and study the correlations between galaxy properties and physical processes.

The student will:

- Identify different galaxy populations in and around galaxy clusters
- Study galaxy properties at z=0, such as gas content, stellar mass and SFR
- Determine the infall time of ancient infallers, recent infallers and backsplash galaxies
- Study the evolution of galaxy properties, and relate them with the environmental processes that affect different populations
- Explore the impact of the dynamical state of the unrelaxed clusters, with respect to the relaxed ones.

Software that will be used: Python, Tensorflow, Pytorch.

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Elias Lopez Asamar & David Cerdeno (UAM)

The Migdal effect: a new channel to search for dark matter

Nearly 80% of the total mass content of the universe can be detected only by gravitational effects. The composition of such matter contribution, called dark matter (DM), is unknown, and there are strong evidences supporting that it is made of a new type of elementary particles. In this context, direct detection experiments aim to find DM particles that might populate the Solar System, by searching for their interactions with a dedicated detector on Earth.

Recently it has been proposed to use the Migdal effect, namely the ionization of an atom when the respective nucleus is perturbed, as a new approach to search for DM in direct detection experiments [1]. However, the Migdal effect currently stands as a theoretical prediction that has not been experimentally verified yet.

This project offers an opportunity to develop some research on the Migdal effect, balancing both theory and experiment. On one hand, the student will review the theory of the Migdal effect, and will work on applying it to DM experiments based on semiconductor detectors, where a proper treatment of the valence electrons is still incomplete. And on the other hand, the student will have the possibility to work in the development of an array of photomultiplier sensors, carried out at the UAM high energy physics laboratory, for the experimental confirmation of the Migdal effect with the MIGDAL experiment [2].

References:
[1] M. Ibe, W. Nakano, Y. Shoji and K. Suzuki, J. High Energ. Phys. 2018, 194
(2018) [2] H. Araújo et al. (MIGDAL Collaboration), arXiv:2207.08284 (2022)

Ivan de Martino & Riccardo Della Monica (Universidad de Salamanca)

"*Using relativistic effects in the Galactic Center to measure departure from General Relativity*"

The Galactic Center (GC) of the Milky Way, thanks to its proximity, allows to perform astronomical observations that investigate physical phenomena at the edge of astrophysics and fundamental physics. As such, it offers a unique laboratory to probe gravity, where one can not only test the basic predictions of general relativity (GR), but is also able to falsify theories that, over time, have been proposed to modify or extend GR; to test different paradigms of dark matter; and to place constraints on putative models that have been formulated as alternatives to the standard black hole paradigm in GR.

The S0-2 star is a B-type star in the nuclear cluster orbiting the radio source SgrA* in the GC of our galaxy. Its orbit is characterized by an orbital period of ∼16 years, a semi-major axis of ∼970 AU and a high eccentricity of ∼0.88. These orbital properties lead to a periastron distance from SgrA* of just ∼120 AU, which is as close as 1400 gravitational radii of the central compact object, and to a pericentre orbital speed of ∼7700 km/s (which is ∼2.5%c), making the pericentre passage of S0-2 a great opportunity to study relativistic effects, as well as to probe the underlying theory of gravity. Future GRAVITY observations of the S0-2 star will be able to detect high-order relativistic effects such as gravitational lensing and Lense-Thirring which will serve as a test bench for GR.

In this TFM, we will want to investigate the impact of these higher-order relativistic effects on constraining departures from GR. Therefore: (1) we need to design a simulated catalogue of future observations of the S0-2 star (or closer astrophysical objects) mirroring the accuracy and precision of GRAVITY; (2) we need to test our the statistical methodology to show that the procedure recovers the input model, to **subsequently** estimate the constraining power of such observations; (3) we may carry out statistical analysis to quantify the accuracy down to which we can measure departures from GR.

Required skills:

- At least, basic knowledge of Python programming
- Basic knowledge of General Relativity

References:

- De Laurentis, M., de Martino, I., Della Monica, R. 2023, Reports on Progress in Physics, 86, 104901. doi:10.1088/1361-6633/ace91b
- Della Monica, R., de Martino, I. 2022, JCAP, 2022, 007. doi:10.1088/1475-7516/2022/03/007
- M. Grould, F.H. Vincent, T. Paumard and G. Perrin, Astron. Astropart. Phys. 608 (2017) A60 [1709.04492].

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Gwendolyn Meeus (UAM)

Exocomets in young stars: link with disc properties?

A circumstellar disc around a star is a natural byproduct of the star-forming process. It is in this disc, made out of interstellar gas and dust, that planets will eventually form. By studying the evolution of those protoplanetary discs (PPD), a lot can be learned about the planet-forming process. In this TFM, we will study the PPD around young intermediate mass stars (2-8 solar masses), the Herbigs and the IMTTS. We will look into their disc geometry and search for clues indicating the presence of a planet. In particular, we will look into red-shifted variable absorption features in their spectra, indicative of infalling material, attributed to exocomets. We will relate the presence/absence of exocomets with other properties of the star and/or disc, such as stellar temperature, metallicity, accretion rate and location of the inner rim.

This TFM will make use of observational data, found in the literature or databases, and basic Python scripts to analyse the data. It is expected that the student takes the course ‘star and planet formation’, in order to prepare for this TFM.

Ignacio Mendigutía & Jorge Lillo-Box, Centro de Astrobiología (CAB, CSIC-INTA)

Looking for companions around young stars with protoplanetary disks from high-resolution imaging

Context and objectives:

It is not clear why the vast majority of stars with spectral type A and B are not single but form part of binary or multiple systems. In order to test whether the observed multiplicity fraction is primordial or not, it is necessary to compare it with that of their precursors, the so called “Herbig” stars. These are intermediate-mass young stellar sources surrounded by protoplanetary disks. However, multiplicity surveys of Herbig stars are scarce and sparse. We have recently conducted a complete survey of Herbig stars, observing all such sources in the northern hemisphere with the AstraLux camera mounted at the 2.2m telescope in Calar Alto Observatory. The resulting high-angular resolution images will be analyzed during this Master thesis project. The final goal is to infer the multiplicity fraction of Herbig stars and compare it with that of main sequence A and B stars. In a second step, the student may lead an observational proposal to extend the survey to the southern hemisphere.

Working place and Supervisors:

The selected candidate will have the opportunity to interact with astrophysicists and engineers in a vibrant, international environment at the facilities of the European Space Agency in Spain (ESA-ESAC, Madrid), working at the Centro de Astrobiología (CAB-CSIC/INTA) building. Such an environment is ideal to get perspective on astrophysics-related career paths, inside or outside academia.

Ignacio Mendigutía has expertise on star and planet formation, with particular focus on Herbig stars.
Personal webpage: https://ignaciomendigutia.wixsite.com/astro
Contact email: imendigutia@cab.inta-csic.es

Jorge Lillo-Box has expertise on the search and characterization of exoplanets and the analysis of AstraLux data.
Personal webpage: https://www.jlillobox.com/
Contact email: jlillo@cab.inta-csic.es

Student's skills:

Real interest and commitment to work on the proposed topic is the only requirement. Very basic knowledge on star/planet formation combined with minimum computing skills are ideal, but the student will be guided in all steps during the process.

Useful links:

Centro de Astrobiología (CAB-CSIC/INTA): https://cab.inta-csic.es/
European Space Astronomy Centre (ESA-ESAC): https://www.esa.int/About_Us/ESAC
AstraLux camera: https://www.caha.es/es/telescope-2-2m-2/astralux

Francisco Najarro, Lee Patrick y Raul Castellanos (Centro de Astrobiología)

Variability of the most massive stars in the Centre of the Galaxy

Massive stars shape their surrounding environments via intense stellar winds throughout their lives and as they explode as supernovae at the end of their lives, which provides chemical and energetic feedback for future generations of stars. Once the most massive stars exhaust their supply of hydrogen in their cores, they go through a variety of short lived stellar phases. Luminous blue variable (LBV) stars represent such a transitional phase in the life cycle of massive stars, which experience large eruptions from their atmospheres expelling large amounts of material in short bursts, and are thought to be progenitors to some of the most energetic supernova explosions known. LBVs are so rare that only a handful are known in the Milky Way and despite their importance, much remains unknown about their evolution. The known examples of LBVs in the Galaxy are often found in extreme environments such as the Central and Quintuplet clusters at the centre of the Galaxy.

Using observational data from the K-band Multi-Object Spectrograph on Very Large Telescope (KMOS/VLT), Chile, the student will study the three LBVs in the Quintuplet cluster and assess how the spectroscopic appearance of LBVs vary over time. The binary nature of the LBVs will be investigated and the consequences of the variability of lack thereof will be put into context in the overall evolutionary cycle of massive stars.

Requirements: This project will involve data reduction and analysis of KMOS/VLT spectroscopic data using well developed recipes. Radial velocities of the stars will be determined and a spectroscopic variability analysis will be performed.

This project will be conducted as part of the Massive Stars research group of the Torrejón site of the Centro de Astrobiología.

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Savvas Nesseris & Marienza Caldarola (IFT UAM-CSIC)

Constraints on modified gravity and the equivalence principle from binary pulsars

One of the earliest, albeit indirect, confirmations of the existence of gravitational waves (GW) emission by accelerating masses, came from the shrinking of the orbit of the Hulse-Taylor binary pulsar, which was found to be in exquisite agreement with General Relativity (GR). Nowadays, GW emissions from binary pulsars provide stringent constraints on deviations from GR at small/ astrophysical scales, due to either covariant modifications of the Einstein-Hilbert action (aka "modified gravity") or violations of the equivalence principle.

In this project, we focus on analyzing Time-of-Arrivals (TOAs) of the pulsars for binary systems, aiming first to reproduce the classic test of GR and then to place constraints on modified gravity models and models predicting violations of the equivalence principle.

The goals of this project are:

1. Understand and familiarize with the theoretical background and the pulsar data. 2.

Extract the necessary information from the data and perform the appropriate modeling.

3. Place constraints on modified gravity models and on models predicting violations of the equivalence principle.

Requisite skills: General Relativity, python.

References:

1. https://www.slac.stanford.edu/econf/C0507252/papers/L004.PDF

2. https://www.aanda.org/articles/aa/pdf/2024/06/aa45246-22.pdf

3. https://arxiv.org/html/2303.17185v2

4. https://arxiv.org/abs/2402.06305

Savvas Nesseris & Indira Ocampo (IFT UAM-CSIC)

Cosmology with Euclid and likelihood data analysis with machine learning

Current and forthcoming surveys are poised to rigorously test the standard cosmological constant and cold dark matter model (ΛCDM) and its underlying principles (e.g. homogeneity and isotropy), as well as possible extensions beyond general relativity (GR), offering unprecedented data quality and volume. In order to test these assumptions, one can perform specific consistency/null tests that require model-independent reconstructions of cosmological parameters and their estimation using minimal assumptions.

In this project, we focus on the Euclid survey and the Baryon Acoustic Oscillations (BAO) data, coming from galaxy clustering, in anticipation of the Data Release 1 (DR1). To analyze these data, the use of the official Euclid likelihood (CLOE) will be explored and ways to modify it consistently in order to extract model-independent quantities, related to the expansion of the Universe.

The goals of this project are:
1) Understand and familiarize with the BAO data and the underlying theoretical framework
2) Explore CLOE and perform some modifications to the likelihood using a non-linear “recipe” for the power-spectrum.
3) Do some preliminary runs and use machine learning to place constraints on deviations from homogeneity and isotropy.

Requisite skills: Basic cosmology, python.

References:
1. Euclid. I. Overview of the Euclid mission, arXiv: 2405.13491
2. Euclid preparation: VII. Forecast validation for Euclid cosmological probes, A&A 642 (2020) A191, arXiv: 1910.09273
3. Euclid: Forecast constraints on consistency tests of the ΛCDM model, A&A 660, A67 (2022), arXiv: 2110.11421

Savvas Nesseris & Martín Rodríguez Monroy

Impact of observational systematic effects on DES-Y3 cosmological parameter estimation with galaxy clustering

Current Stage-III surveys and next generation Stage-IV surveys are shrinking statistical uncertainties to unprecedented levels in cosmology. This is allowing us to do stringent tests to the standard cosmological model (ΛCDM) and to set tight constraints on the values of the parameters that describe this model. However, given the low statistical errors, the previously subdominant systematic effects are becoming the main source of uncertainty, making it crucial to thoroughly understand them and to properly correct them from the data. In this sense, one of the main sources of uncertainty are the so-called observational systematics.

In this project, we focus on the Dark Energy Survey (DES) and the angular correlation function for galaxy clustering, $w(\theta)$, measured on the data from its third data release (DES-Y3). The other aspect that we focus on is the impact of observational systematics on the measured signal of $w(\theta)$ and how it affects the inference of different parameters, such as ΩM or the galaxy bias.

The goals of this project are:

1. Understand and familiarise with the angular correlation function and the underlying theoretical framework.
2. Understand the different sources of observational systematics and their nature.
3. Compute $w(\theta)$ on DES-Y3 data to evaluate the impact of different observational systematics on it.
4. Do some preliminary runs to set constraints on Ωm and the galaxy bias from data affected by different systematic effects.

Requisite skills: Basic cosmology, python.

References:

Dark Energy Survey Year 3 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing, Phys. Rev. D 105, 023520 (2022), https://arxiv.org/abs/2105.13549
Dark Energy Survey Year 3 Results: Galaxy clustering and systematics treatment for lens galaxy samples, MNRAS, 511, 2, (2022), https://arxiv.org/abs/2105.13540

Nataly Ospina & Luis Labarga (UAM) *Search of the DSNB with Super-Kamiokande*

Core-collapse Supernovae (CCSNe) are among the most catastrophic phenomena in the Universe and are essential elements of the Cosmos. However, their underlying mechanism is not understood; characterizing it would require complex knowledge of the core of the collapsing star. This information could be accessed by detecting neutrinos emitted in the Supernova, whose luminosity and energy spectra closely follow the different steps of the CCSNe mechanism.

The existing neutrino experiments are mostly sensitive to SNe occurring in our galaxy and its immediate surroundings, but, nevertheless, these events are extremely rare (a couple of times per century in our galaxy). An alternative way to learn about the properties of SNe in the Universe is to study the neutrinos that have been emitted by each SNe since the beginning of the formation of the Universe. The integrated flux of these neutrinos forms the "Diffuse Supernova Neutrino Background" (DSNB), also known as "Supernova Relic Neutrinos" (SRN). If they could be detected, they would provide a steady stream of information on stellar collapse, nucleosynthesis, formation of the heavier elements, and determination of the rate of optically failed SNe by comparison with optical measurements. Also, as the DSNB is composed of neutrinos of all flavors whose energies have undergone a redshift during their propagation toward the earth, on the size and nature of the evolution of the Universe itself.

The student will be involved in the analysis of the search of the DSNB with the Super-Kamiokande (SK) Gadolinium (Gd) data. SK is one of the most important neutrino experiments in the world and, since 2020 started the Gd phase. It consists in the addition of Gd salt to the SK water to improve the sensitivity of the detector. There are several theoretical models for the DSNB; their predictions for the flux vary within a factor 10; now according to the most widely accepted modern analyses (Horiuchi et al. 2009, Beacom 2010), SK with Gd2(SO4)3 (2% solution) should detect up to six such SNe events each year.

References:

The Super-Kamiokande Collaboration; Harada, M. et al. 2023; Search for astrophysical electron antineutrinos in Super-Kamiokande with 0.01wt% gadolinium-loaded water, eprint arXiv:2305.05135.

Giampaolo, A. et al. 2022; Diffuse Supernova Neutrino Background search at Super-Kamiokande with neutron tagging, 37th International Cosmic Ray Conference. Online, published March 18, 2022, id.1154.

The Super-Kamiokande Collaboration; Abe, K. et al. 2021; Diffuse Supernova Neutrino Background Search at Super-Kamiokande, Physical Review D, 104, 12, article id.122002

Lee Patrick (Centro de Astrobiología)

Studying the runners:
Characterising Red supergiant runaway stars in the Magellanic Clouds using Gaia

Massive stars are those which end their lives in violent supernova explosions. In such explosions massive stars redistribute material that they have processed throughout their lives and pollute their surrounding environment. Through this process, these stars are responsible for many of the chemical elements that we observe in the Universe today.

We now know that the majority of massive stars are born within binary systems. How these stars interact with their companions is key to determining how they end their lives. Runaway stars are those that have been kicked out from binary systems after a supernova explosion or interaction with another star. We see many such stars in early evolutionary phases, but at the final evolutionary stage - the red supergiant phase - no confirmed runaway has been identified outside of the Milky Way.

This is partly because until the most recent Gaia data release (DR3; June 2022) such stars have been very difficult to identify. With Gaia DR3, proper motions from earlier releases have been supplemented with an additional radial velocity component, which allows one to study the dynamics of these galaxies in greater detail. Given what we know about the evolution of massive stars, how does binary evolution contribute to the dynamics of the red supergiant population of the Magellanic Clouds?

In this project the student would make use of the most recent Gaia data release to study the dynamics of the Large Magellanic Cloud - one of our nearest neighbour galaxies - using red supergiant stars and identify the first red supergiant runaway stars outside of our Galaxy. A dynamical model will be obtained for this galaxy and compared with other tracers of dynamical evolution.

The student will then use this model to identify outliers. In this sense, this will be the first homogenous study of runaway red supergiant stars in the Large Magellanic Cloud. Using simulations, the student will estimate the total number of red supergiant runaways in this galaxy. Time permitting, the student may compare these results to evolutionary models to test the physics of binary evolution.

Requirements: This project will be based on Gaia DR3 data which will be downloaded and analysed by the student. Some knowledge of python would be useful, but the main criteria is an interest in the project.

This project will be conducted as part of the Massive Stars research group of the Torrejón site of the Centro de Astrobiología.

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Lee Patrick (Centro de Astrobiología)

A chemical map of Red supergiant stars in the Perseus OB-1 association

Red supergiant stars are the final evolutionary stage of the majority of massive stars before a supernova explosion. These stars are extremely useful to test theories of stellar evolution, particularly when they occur in star forming associations of fixed ages. The Perseus OB-1 association is one of the closest such examples to Earth and therefore acts as an excellent laboratory for detailed studies of red supergiant stars.

We have recently obtained high-resolution spectroscopic observations from the Mercator Telescope of all 20 of the red supergiants in Perseus OB-1 association with the aim of searching for binary systems and determining chemical abundances for the targets.

The observations are fully reduced. The student will lead the analysis to determine stellar parameters by developing and applying chemical analysis routines (based on existing routines) using state-of-the-art stellar evolutionary models. The student will generate a grid of models that cover the range of expected parameters and use a minimisation technique to determine the stellar parameters that best describe the observations.

The student will compare the results with abundance measurements in the literature and quantitatively assess the recent claims of extreme chemical homogeneity (Fanelli et al. 2022), which needs to be independently verified.

This project will be conducted as part of the Massive Stars research group of the Torrejón site of the Centro de Astrobiología.

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Lee Patrick (Centro de Astrobiología)

Bi-modal metallicity distribution of the IC 1613 galaxy

IC 1613 is a low-metallicity dwarf irregular galaxy with a controversial metal abundance. Recent studies using Blue Supergiant stars suggest that this galaxy contains an intriguing, bimodal metallicity distribution. By determining metallicities of ~40 Red Supergiant Stars (RSGs), using the well tested J-band analysis technique, the student will independently estimate the metallicity distribution of IC 1613 and examine the hypothesis of bimodality.

Spectroscopic observations using the K-band Multi-Object spectrograph on the Very Large Telescope have been obtained. The student will reduce and analyse these data, using a well defined reduction recipe. Using a grid of stellar models the student will determine the effective temperature, metallicity and surface gravity of each star and study the metallicity distribution of IC1613.

Requirements: This project will involve data reduction of near-infrared spectroscopic observations, which require a basic level of coding ability. Coding scripts to perform the spectral fitting may also be developed within python.

This project will be conducted as part of the Massive Stars research group at the Centro de Astrobiología.

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Lee Patrick (Centro de Astrobiología) & Jesús Maíz Apellániz (Centro de Astrobiología ESAC)

Photometric variability of RSGs in the MCs

Red supergiant stars (RSGs) are the final evolutionary stage of the majority of massive stars before a supernova explosion. When a massive star stops burning hydrogen into helium in its core, the star drastically expands its outer envelope and appears as an RSG. Despite their importance for understanding the diversity of observed supernovae, the physics of the atmospheres of RSGs is incomplete, which has implications for our understanding of how much mass massive stars lose throughout their lives and ultimately what the final supernova explosion looks like. Studies of the physics of RSGs have previously focused on individual systems and a complete picture of how variable the atmospheres of RSGs is lacking.

New results from the Gaia mission (DR3; June 2022) allows the study of stellar variability in different evolutionary phases for entire populations of stars in the Magellanic Clouds: two of our nearest neighbour galaxies. In this project the student will study the variability of RSGs in the Magellanic Clouds using a new catalogue of variability based on Gaia DR3. Global trends will be studied and a relationship between evolutionary phase and variability will be developed. The student will analyse this large dataset and use this to place in context the recently observed Great Dimming of Betelgeuse.

Requirements: This project will be based on Gaia DR3 data which will be downloaded and analysed by the student.

This project will be conducted as part of the Massive Stars research group at the Centro de Astrobiología.

For more information contact: lrpatrick at cab.inta-csic.es

Enrique Perez & Ruben Garcia-Benito (IAA), Angeles Diaz (UAM)

Re-evaluating the evolution of the mass-metallicity relation in the VIPERS survey

The mass-metallicity relation (MZR) is one of the most fundamental relations for star-forming galaxies and implies that there is a correlation between the integrated stellar mass and the metal content of these objects. Among the different aspects still under investigation in relation with the MZR are its evolution with redshift and the secondary dependence with star formation rate (SFR).

For this reason, there are an increasing number of deep surveys intended to enlarge the number of galaxies at different cosmological epochs to find more precise answers to these issues.

Among these surveys, VIPERS have compiled spectroscopic information about around 10k objects in the redshift range $0.3 < z < 1.0$.

Metallicity is usually estimated in most works deriving the total oxygen chemical abundance from very simple relations between the flux of certain emission-lines in the local Universe. We have proposed a new method based on photoionization-models that makes use of all available information in a consistent way. The proposed work consists of a re-evaluation of the conclusions made by the VIPERS collaboration in what regards to the evolution of the MZR, using our new method to derive the metal content of the analyzed VIPERS galaxies. The new method will use as input the available information of the main lines emitted by the ionized gas, comparing the results with what has been already published by this collaboration.

Enrique Perez & Ruben Garcia-Benito (IAA), Angeles Diaz (UAM)

Statistical Study of the Radial Variation of the Effective Temperature of Ionizing Clusters in MaNGA Sample Galaxies

MaNGA (Mapping Nearby Galaxies at Apache Point Observatory) is a survey of over 2000 galaxies in the nearby universe, conducted in the optical part of the spectrum using the technique of integral field spectroscopy. This technique allows for obtaining maps with a spatial resolution of about 2.5 arcseconds of all the spectral features.

In this work, we propose to use the database containing the main emission lines produced in the brightest star-forming regions of MaNGA's disk galaxies and utilize a Python-based code to transform that observational information into characteristics of these regions, including their metal content, ionization parameter, and the equivalent effective temperature of the ionizing clusters. The aim is to analyze whether the radial variation of these properties along the galaxies' disks is correlated with other integrated properties, such as their brightness, mass, or morphological type. The study of these characteristics in a large sample is crucial for understanding the formation and evolution mechanisms of these objects.

Given the large amount of data to be processed, as well as the need to use Python to execute the necessary codes for deriving part of the information, it is required that the student has knowledge of Python or similar programming languages.

Isabel Rebollido (CAB)

Delivery of volatile materials in planetary systems with JWST

The presence of water on Earth challenges the models of planet formation, as volatiles are expected to be depleted in the inner regions of planetary systems in the early years of their evolution. Multiple hypothesis suggest an external origin, as comets and asteroids bombarded the surface of rocky planets while the system was dynamically unstable. If this were the case, we can search for similar mechanisms taking place in young forming exoplanetary systems.

Exocomets that can be polluting the surfaces and atmospheres of planets have been detected for decades, but it is now, with the advent of JWST, that we can observe volatile materials in the warm and hot regions of planetary systems, including CO and H2O.

The tasks in this project will include data reduction and analysis of a JWST NIRSpec spectra of a exocomet host star, to search for volatiles and establish upper limits. If the analysis is completed, the results could be submitted to a scientific journal.

The student is required to have a good level of English (both in speaking and writing), and programming skills in python.

Dynamical evolution in the galaxy of planet hosting stars

Isabel Rebollido (ESA), María Luiza Linhares Dantas (Universidad Católica de Chile)

Planets are ubiquitous in our Galaxy, with almost every star expected to have a planetary system. There is a prevalence of giant planets particularly around metal rich stars, which seems to be connected to the formation mechanism. Moreover, these planets are in a lot of cases hot Jupiters, meaning they are particularly close to their host star.

Recent studies have found evidence of stars migrating through the Galaxy as they evolve, allowing for high-metal rich stars to be found in the solar vicinity (Dantas et al. 2023). There is evidence that our Sun might have also migrated Tsujimoto & Baba (2020).

We propose here a search for planets around stars that have migrated, and to investigate the properties and orbital characteristics of such planets.

The student will have to cross match archives, search the literature and perform statistical analysis of the results. If time allows, the student will also characterize these metal-rich stars (e.g. spectral model fitting). If no planets are found, the student will have to write a proposal to search for planets in the sample of stars with either ground base or space based (or both) telescopes, depending on the stellar characteristics.

A paper is expected to come out of this research.

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Investigating the lack of exo-moons

Isabel Rebollido (ESA)

Most planets in the Solar System have one or more moons, with the exception of Venus and Mercury. The fact that despite the growing sensitivity of space missions we have not found any exomoons is intriguing, and arises the question of how common satellites even are.

We propose a study of a possible correlation between the location of planets that have been searched for moons and how it compares to the location of moons in our Solar System. The student will have to investigate the publications about exomoons (recent and past) to create a catalogue of planets that have been searched, and include all the known characteristics about said planets (orbit, mass, stellar characteristics, etc). This would ideally be hosted on Github and made available publicly so it can become a collaborative tool.

Additionally, we will investigate any correlation between the possible migration of planets and the presence of moons, including the dynamical past of Mercury and Venus, and whether that might have influenced their lack of satellites.

A paper is expected to come out as a result of this research.

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Miguel Sanz-Novo (CAB) and Víctor M. Rivilla (CAB)

Pushing the limits of chemical complexity in the interstellar medium: Branched molecules as a pathway to prebiotic chemistry

In recent times, large organic molecules of exceptional complexity have been found in diverse regions of the interstellar medium (ISM). In this context, the identification of branched-chain species in the ISM is a crucial link between the molecular inventory of the Milky Way and the chemical composition of small celestial objects (e.g., comets and asteroids, as well as meteorites), in which several branched-chain amino acids have been found. This TFM project will focus on the detection and study of branched organic molecules, like iso-propyl cyanide (i-PrCN), in the Galactic Center molecular cloud G+0.693-0.027, one of the richest astronomical sources in our galaxy. The research aims to connect the formation of these species with pathways that may lead to the formation of amino acids such as isovaline and leucine, which are key molecules in prebiotic chemistry.

Methodology:

- The student will be trained in rotational spectroscopy applied to the study of astrophysically relevant species to prepare line catalogues to search for branched species. in the ISM.
- The student will analyze existing spectral data from surveys conducted in chemically rich clouds, using modern astrophysical analysis tools like MADCUBA, to identify rotational transitions of branched molecules and obtain their relevant physical parameters (molecular column densities, line widths, etc.).
- The student will investigate the formation mechanisms of these molecules and their possible connection to prebiotic chemistry (i.e, amino acids) using chemical networks that are available in the literature.

Main expected outcomes:

- First or second detection in the ISM of several branched molecules in the G+0.693 region and derivation of the normal-/iso- ratio.
- Contribution to the understanding of the chemical complexity and potential prebiotic chemistry occurring in the ISM.

This project will be conducted at the Centro de Astrobiología (CAB-CSIC/INTA), a joint research center affiliated with both the Spanish National Research Council (CSIC) and the National Institute for Aerospace Technology (INTA), specifically within the “Chemical Complexity in the ISM and Star Formation” group (website: https://cab.inta-csic.es/astrochem/index.html).

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Miguel Sanz-Novo (CAB) and Víctor M. Rivilla (CAB)

Toward the detection of water complexes in the interstellar medium

In recent years, significant endeavors have been made to study the molecular complexity of the interstellar medium (ISM). Astrochemistry has shown that interstellar chemistry is able to generate different complex organic molecules (COMs), which are carbon-based molecules comprised of 6 or more atoms, highlighting several building blocks of key biomolecules. Given that water is a fundamental ingredient for life, and it is highly abundant in the ISM, a very intriguing question arises. Are weakly bound van der Waals COMs-H2O clusters expected to form in the ISM? We expect that they would be complicated to form entirely in the gas-phase, given that the rate of three-body association reactions is relatively small for small molecules. But, in principle, it would be possible that these water clusters could form in amorphous icy grain mantles and be desorbed due to shocks. Thus, they should be present in prominent sources such as the chemically rich Galactic Center molecular cloud G+0.693-0.027, where desorption is shock-dominated. Within this framework, this TFM project aims to investigate the formation and detection of molecular complexes involving water (H2O) in the ISM. Particularly, we plan to investigate and search for several abundant 1:1 COMs-H2O clusters related to ubiquitous interstellar molecules, starting with methylcyanide-H2O, methanol-H2O, ethanol-H2O, which have already been characterized in the laboratory by microwave spectroscopy but have not been searched for in the ISM.

Methodology:
- The student will be trained in rotational spectroscopy applied to the study of astrophysically relevant species to prepare line catalogues to search for branched species. in the ISM.
- The student will analyze existing spectral data from surveys conducted in chemically rich molecular clouds, using modern astrophysical analysis tools like MADCUBA, to identify rotational transitions of water complexes and obtain their relevant physical parameters (molecular column densities, line widths, etc.).
- The student will investigate potential chemical pathways for the formation of these complexes through a combination of observational data and chemical modeling.

Main expected outcomes:
- Identification of water complexes of simple and very abundant molecules. In the case of nondetections, upper limits to their molecular abundance will be derived.
- Insights into the role of water in prebiotic chemistry within the ISM.

This project will be conducted at the Centro de Astrobiología (CAB-CSIC/INTA), a joint research center affiliated with both the Spanish National Research Council (CSIC) and the National Institute for Aerospace Technology (INTA), specifically within the "Chemical Complexity in the ISM and Star Formation" group (website: https://cab.inta-csic.es/astrochem/index.html).

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Richard Saxton (ESAC) and Erwan Quintin (ESAC)

Production of an on-line UV long-term light curve generator

Description:

One of the key current topics in astronomy is the search for transient and highly-variable objects, which open up a new window into exploring phenomena such as Tidal Disruption Events and Changing-Look AGN. Our group has developed an on-line tool (HILIGT; 1,2) which produces a long-term light-curve of the X-ray flux of an object using many of the current and historical X-ray facilities. In this project, the student will build a similar tool, dedicated to creating light-curves in the ultraviolet band. Such a general purpose tool, capable of comparing fluxes from many ultraviolet observatories does not currently exist and has the potential to uncover new classes of transient sources.

The project will involve gaining an understanding of the calibration of UV cameras such as Swift UVOT, XMM-OM, GALEX, EUVE and other space-based UV photometric experiements. Work will then be needed to derive cross-calibrations between these instruments in cases where this does not yet exist, so that the measured fluxes can be directly compared.

The student will learn how to program scientifically with Python, Javascript and REST technologies. They will learn about UV astronomy, the magnitude systems, conversions from magnitude to flux and the systematic errors which need to be taken into account when cross calibrating instruments from different missions. If time permits the finished tool will be used to make an initial search for interesting highly-variable UV objects.

The project will be conducted with members of the ESAC science faculty

(https://www.cosmos.esa.int/web/space-science-faculty/sites/esac).

For more information contact Richard Saxton (richard.saxton@ext.esa.int)

Desirable skills:

- Python programming
- Understanding of astronomical magnitudes
- A basic knowledge of different classes of astronomical source

References:

(1) Saxton et al. "HILIGT, upper limit servers I-Overview", 2022, Astronomy and Computing, 38, 100531

(2) Koenig et al. "HILIGT, Upper Limit Servers II - Implementing the data servers", 2022, Astronomy and Computing, 38, 100529

Pedro de la Torre Luque & Miguel A. Sánchez Conde (UAM)

"Molecular clouds as a tool to constrain the existence of sub-GeV DM in the Galaxy"

Descrip(on:

The nature of dark matter (DM) remains one of the most intriguing mysteries in physics nowadays. Despite the efforts to search for signatures of weakly interactive massive particles (WIMPs), no evidence has been found yet. This has motivated the search for extensions of the WIMP paradigm. Recently, the thermal production of DM particles with mass below ~100 MeV have been proposed as an interesting alternative that could explain the anomalous emission of 511 keV photons at the Galactic centre as well as the unexpected high ionization rate in the central molecular zone.

Here, we investigate for the first time whether molecular clouds can effectively be used to constrain the existence of sub-GeV DM particles. We will evaluate the ionization rate caused by sub-GeV DM annihilating into Standard Model particles, for molecular clouds located in different regions of the Galaxy. Furthermore, the ionization rate caused by the direct interaction of DM particles with the gas in the molecular clouds will be studied and used to constrain the coupling of the DM particles with electrons.

This TFM will be carried out within the boundaries of the DArk Matter, AStroparticles and COsmology (DAMASCO) group at the UAM Theoretical Physics Department and the Institute for Theoretical Physics (IFT UAM-CSIC). DAMASCO's current main research interests include the indirect search for dark matter, with special care to gamma rays; the analysis of numerical cosmological simulations, mainly to shed light on the smallest scales; high-energy neutrino astrophysics; cosmic-ray astrophysics; multi-messenger astronomy. DAMASCO belongs to the Fermi-LAT Collaboration, the Cherenkov Telescope Array (CTA) Consortium, and the DESI Collaboration. The group has also an excellent network of collaborations with (local, national, international) experts in astroparticle physics and cosmology.

Further info about the team and research activities: https://projects.ift.uam-csic.es/damasco/

Required skills:

- Good programming skills (python)
- Good English level

References:

- Phan et al. Monthly Notices of the Royal Astronomical Society, 480, 5167–5174 (2018), doi:10.1093/mnras/sty2235
- Padovani et al. Astronomy & Astrophysics 501, 619–631 (2009), doi:10.1051/0004-6361/200911794
- De la Torre Luque et al, Astrophysical Journal. 968 (2024) 1, 46, doi: 10.3847/1538-4357/ad41e0
- De la Torre Luque et al. (2023) arXiv: 2312.04907

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Luis Velilla Prieto (Dept. of Molecular Astrophysics. Instituto de Física Fundamental, CSIC)
Molecular complexity in the rapidly evolving star V Hydrae

Stars in their late stages of evolution play an important role in the enrichment and replenishment of synthesized material in terms of gas and dust. In particular, Asymptotic Giant Branch (AGB) stars are amongst the top contributing sources to the chemical complexity growth and the enrichment of the interstellar medium. These stars produce vast amounts of molecular gas and dust grains that form dense circumstellar envelopes that are further processed due to photochemical processes, shocks, gas-grain interactions, and more. Interestingly, a rapid evolution seems to take place once they evolve through the post-AGB stage in their way to form a planetary nebula.

Recently, we have found an increasingly complex chemistry in the outflows of these post-AGB stars which is probably caused by shocks as a consequence of binary interaction. In order to advance our understanding about this chemical complexity, we aim to investigate the molecular content of post-AGB objects using spectra of these outflows in the millimeter wavelength range. In this work, we propose to study a spectral line survey carried out with the Atacama Pathfinder Experiment (APEX) antenna of the carbon rich post-AGB star V Hydrae. We will use standard reduction and analysis techniques with the software CLASS (GILDAS https://www.iram.fr/IRAMFR/GILDAS/) to identify spectral lines and characterize the circumstellar envelope of this puzzling object.

A good command of English is highly recommended as well as programming skills (any language is good, Fortran, Python, or even knowledge with Matlab).

References:

[1] https://arxiv.org/abs/1412.2074

[2] https://arxiv.org/abs/1609.01904