Bachelor thesis project suggestions, astrophysics

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These suggestions should form a starting point for discussions with your possible supervisors.

1 How can we identify extragalactic stars in the Milky Way?

Background: Stellar spectroscopy deals with the extraction of astrophysical information from spectra of stars. Accurate analyses of stellar spectra enables us to determine the abundances of elements in stars, which can provide clues to questions like the origin of the elements and the origin and evolution of galaxies! Stellar atmosphere theory and models, as well as the theory of line formation, is fundamental for this field.

Aims: In this project you will investigate how well one can determine the abundance of Manganese (Mn) from near-IR, high-resolution APOGEE spectra of giants. The Mn abundance can be used in combination with the abundances of Mg and Al to identify extragalactic, accreted stars. For this, a precise and accurate Mn determination is needed, which now is possible.

Methods: In the framework of this Bachelor's Thesis project in stellar spectroscopy, you investigate how well we can determine the abundance of Manganese from near-IR, high-resolution APOGEE spectra at the highest possible accuracy and precision. You will then evaluate the possibility to identify extragalactic stars spectroscopically. You will be trained in stellar spectroscopy, and in the interpretation and synthesis of stellar spectra based on calculated stellar atmospheres.

It would be advisable to have attended or attend the Spring course ASTA34, Stellar atmospheres and radiation processes.

Supervisors: Govind Nandakumar (govind@astro.lu.se) and Nils Ryde (ryde@astro.lu.se)

References:

- Jönsson et al. ApJ, 160, 120 (2020)
- Vasini et al. (2023). https://arxiv.org/abs/2310.04530

2 Infrared dwarfs

Aims: The central region of our galaxy, referred to as the bulge, is an enigmatic region. It is unclear whether it is a unique population of its own or a conglomerate of the other Galactic stellar populations. With the recent studies of microlensed dwarf stars in the bulge it was for the first time possible to determine ages for individual stars in the bulge. Contrary to what was previously thought, that the bulge population was all old, it was now discovered that the bulge contains a significant fraction of young stars. As the bulge region is heavily extincted, and since the spectra of the microlensed dwarfs were observed in the optical, it was not possible to get closer than 2-3 degrees from the Galactic plane. Hence the age structure of the inner bulge region is not known. New microlensing data of dwarf stars in the infrared will help us to go deeper into the bulge. In preparation for that we need to investigate and explore the best ways to determine stellar parameters from infrared spectra for dwarf stars. This cannot be done in the same way as it is done for spectra in the optical, and it cannot be done in the same way as for giant stars. Accurate stellar parameters, in particular surface gravity and effective temperature, are crucial when estimating stellar ages from isochrone fitting. The aim of this project is to explore different analysis methods to determine stellar parameters, and how they are affected by the quality of the spectra (SNR), and the metallicity of the stars.

Methods: The project requires programming skills in python as the tools we will use are written in that language, in particular the spectral synthesis code PySME that will be the main tool. We will make use of both synthetic spectra, created with PySME, and also look for real spectra of dwarf stars in the ESO archive, and from the CRIRES+ spectrograph in particular.

Supervisor: Thomas Bensby (thomas.bensby@fysik.lu.se)

References:

- D.F. Gray - The observation and analysis of stellar photospheres

3 The impact of angular momentum on the stellar mass and stellar density of galaxies

Background: Recent studies have suggested that the star formation of galaxies evolve son two different tracks. In a stellar vs. central stellar mass density plot, the galaxies with highest central stellar density evolve by increasing even more their central density. On the other hand, galaxies with underdense centres see their stellar mass increase faster than their stellar mass. One possible origin of this mechanism is the angular momentum content of the accreted material: low angular momentum accretion allow the gas to pile up at the centre, increasing the central density, while high angular momentum results in extended star formation, forming stars in the outskirts (hence the central density doesn't increase much).

Aims: You will measure the central stellar density and stellar mass for three galaxies where we systematically varied the accreted angular momentum (each galaxy is simulated in 5 different scenarios; see Cadiou, Pontzen & Peiris 2022). By comparing how these galaxies evolve on a stellar mass vs. central stellar density diagram, you will be able to assess how individual galaxies move in the mass-density diagram and confirm or infirm the role played by angular momentum.

Supervisors: Corentin Cadiou (corentin.cadiou@astro.lu.se) and Oscar Agertz (oscar@astro.lu.se)

4 Unveiling the nature of dark matter using intra-halo light

Background: Since the early 20th century, we have known that the formation and evolution of galaxies are dominated by exotic matter, interacting with regular matter only through gravity. This phenomenon is what we refer to as dark matter. In recent years, with high-quality observations of the kinematics and dynamics of stars within galaxies, as well as observations of galaxies themselves over cosmic time, the most accepted theory for dark matter—known as Cold Dark Matter (CDM)—has encountered numerous challenges. Some of these challenges stem from discrepancies between observations and simulations when studying satellite galaxies, stellar streams, and the diffuse light surrounding central galaxies (intra-halo light). Currently, many research groups are actively working on producing new simulations that vary the nature of dark matter to determine which model best fits the observations.

Among these groups, the ARRAKIHS WPS6 team, led by Prof. Oscar Agertz and Dr. Santi Roca-Fàbrega in Lund, with the participation of all other members in the 'Galaxy Formation and Evolution group,' is generating a large set of cosmological simulations of Milky Way-like galaxies. These simulations aim to test different dark matter scenarios.

Aims: In this project, the student will analyse simulations of galaxy formation within the context of the AGORA [1] and ARRAKIHS [2] collaborations. The goal is to understand how different flavours of dark matter influence the distributions of stars and dark matter in the surroundings of galaxies. Specifically, the work will focus on the study of intra-halo light (stellar particles in this case) and the dark matter distribution in the halos of those galaxies, excluding sub-halos and satellites. The main goals of the project will be:

1. Learn how to use the 'yt' python module to read and analyse simulations.
2. Read simulations from the AGORA suite and obtain radial profiles and global properties for the stellar and dark matter components in the galaxy outskirts.
3. Compare the results obtained from the different simulations.
4. Analyse simulations obtained with different dark matter flavours and obtain the same parameters as in bullet number 2.

5. Identify differences and similarities between the results obtained in the different simulations analysed.

For this project, the student should have good programming skills. Specifically, it is important that the student has proficiency in python and has an interest in the theory of galaxy formation and evolution.

Supervisors: Tilly Evans (tilly.evans-hofmann@fysik.lu.se), Santi Roca-Fàbrega (santi.roca_fabrega@fysik.lu.se)

5 Investigating crowding in the Galactic centre and Galactic plane for GaiaNIR.

Background: The Gaia spacecraft is a space astrometry mission, operating in the optical G band and is currently making measurements that are revolutionising our understanding of the Galaxy. A successor mission called GaiaNIR is now being planned which will extend the wavelength range into the Near InfraRed (NIR) up to 2.5 μm or K-band. A new all-sky NIR astrometric mission will expand and improve on the science cases of Gaia using basic astrometry. Key topics are focused on what dark matter is and how is it distributed, how the Milky Way was formed and how has it been impacted by mergers and collisions. How do stars form and how does stellar feedback affect star formation; what are the properties of stars, particularly those shrouded in hidden dusty regions, how are stars distributed and what is their motion.

A serious problem for this new mission is crowing in dense regions of the sky and it is necessary to make maps to assess where this will be a serious problem. In some particularly dense regions of the sky crowding will mean that stars will overlap each other making astrometry difficult given the telescopes designed resolution. This needs to be assessed for the complete wavelength range and for various filters bands within the full wavelength range of the survey to give a complete picture of the crowding issues.

Aims: The student will investigate how to assess crowding issues using the Besançon Galaxy model. This is already available for the Gaia G-band and the student should reproduce those results. The student will then investigate how to change the wavelength range and then apply the same method to the broader wavelength range proposed for GaiaNIR (i.e. 0.8-2.5 μm). The student will also simulate different, narrower, filter bands which may be used for the photometry measurements. The results will be an assessment of the crowding issues that GaiaNIR will face and they could be used to improve the mission design.

Methods: The student will use the Besançon Galaxy model to extract small patches of the sky in the Galactic centre and the Galactic plane to give estimates of the number counts and angular separation of stars in the Gaia G-band and then extend this up to the K-band. The data can then be used to assess what GaiaNIR can resolve in these regions and allow conclusions to be drawn concerning crowding issues for the mission.

Supervisor: David Hobbs (david.hobbs@fysik.lu.se)

References:

- The Besançon Galaxy model and references can be obtained here: https://model.obs-besancon.fr/ and here https://model.obs-besancon.fr/ws/
- Hobbs et al., Experimental Astronomy volume 51, pages 783–843 (2021) (https://link.springer.com/article/10.1007/s10686-021-09705-z)

6 Variability of white dwarf debris discs

Background: White dwarf stars are the end state of stellar evolution for stars like the Sun. They are the cooling remnant of the stellar core, after nuclear fusion has ceased and the star's envelope has been lost. Many white dwarfs exhibit an infrared excess, showing the presence of cooler material in orbit around the star. Often, these excesses are consistent with a dusty disc close to the white dwarf, thought to arise from the disruption of asteroids close to the star. The infrared excesses are often variable in time (Swan et al., 2019), suggesting that processes in the disc are changing the amount and/or geometry of the dust disc; these processes may include collisions between asteroid fragments.

Aims: As well as affecting infrared emission, a dust disc should also affect the amount of light seen in visible wavebands, by reflection, scattering, or occultation of the white dwarf. A variability in the amount or configuration of the dust should therefore also cause a variability in the brightness of the white dwarf in the optical. The student will attempt to calculate the expected optical variability corresponding to typical observed infrared variability. The theoretical results will be compared to observations of white dwarfs being performed by Dr J. Korth.

Methods: The student will construct geometrical models of the dust discs surrounding white dwarfs, and calculate (analytically or numerically) the flux at optical and infrared wavelengths as the properties of these discs change. Programming is expected to be performed in Python.

Supervisors: Alexander Mustill (alexander.mustill@fysik.lu.se) and Judith Korth (judith.korth@fysik.lu.se)

Reference:

- Swan, Farihi & Wilson, 2019, MNRAS Letters, 484, L109 https://ui.adsabs.harvard.edu/abs/2019MNRAS.484L.109S/abstract

7 Estimating stellar limb darkening using exoplanet transits

Background: Stellar limb darkening is an optical effect seen in stars (including the Sun), where the central part of the stellar disk appears brighter than the edge, or limb. It plays an important role in the analysis of many astrophysical data (e.g. transiting exoplanets and eclipsing binaries). Both stellar and exoplanet science could benefit from the improvement of its understanding but direct measurements of limb darkening can be carried out only on the Sun. Stellar limb darkening is among the main challenges to getting the planetary radius with high accuracy from a small number of transits of small planets. Limb darkening modifies the transit depth by a factor of two relative to the case when there is no limb darkening. Limb darkening coefficients can be determined simultaneously with the planet-to-star radius ratio if the signal-to-noise ratio (S/N) is sufficiently high, such as what can be reached with space-based telescope like CHEOPS.

Aims: The student will estimate the stellar limb darkening for a set of bright transiting exoplanets (hot Jupiters) using publicly available transit light curves observed by the CHEOPS space telescope.

Methods: The student will download the CHEOPS light curves from Dace (https://dace.unige.ch/dashboard/) and model the transits using PyCHEOPS (Maxted et al. 2022) available on GitHub (https://github.com/pmaxted/pycheops) to obtain the stellar limb darkening estimates. The project requires basic knowledge of Python.

Supervisors: Judith Korth (judith.korth@fysik.lu.se) and Alexander Mustill (alexander.mustill@fysik.lu.se)

References:

- Maxted et al. (2022), MNRAS, Volume 514, Issue 1, pp.77-104

8 Validation of Exoplanets exhibiting dynamical interaction

Background: Exoplanets, or extrasolar planets, are celestial bodies that orbit stars outside of our solar system. One way to search for them is through their signature when they transit their host star. The Transiting Exoplanet Survey Satellite (TESS) is currently conducting an all-sky survey and discovering a high amount of new exoplanet candidates. The validation of exoplanet candidates, confirming their existence and nature as a planet, has been a monumental task that has unfolded over the past few decades. Several approaches are used for this including radial velocity measurements, multi-color photometry, and statistical methods. The latter one uses only the information that is already given when TESS observes the target.

Aims: To explore the impact of orbit perturbations on the likelihood of exoplanet candidate signals, the student will employ TRICERATOPS, a powerful Python tool designed for exoplanet validation. TRICERATOPS evaluates the probability of a candidate signal being authentic by assuming a strict periodicity in the observed transit signals. If instead, the orbit of the exoplanet candidate is perturbed, the strict periodicity is broken. The student should study if such perturbations change to likelihood of the exoplanet candidate signal and if does to what extent. The study is anticipated to reveal insights into the robustness of TRICERATOPS in the presence of orbit perturbations. It will provide a nuanced understanding of how variations in the orbital dynamics of exoplanet candidates influence the probabilistic validation outcomes.

Methods: The student will use the Python tool TRICERATOPS to validate exoplanet candidates from the TESS mission that exhibit signs of orbit perturbations. Such perturbations can arise from various factors, including gravitational interactions with other celestial bodies. The student will utilize available data on these candidates, including their light curves and other relevant observational parameters provided by TESS. Subsequently, the student will input this information into TRICERATOPS to assess the impact of orbit perturbations on the validation process. By comparing the results obtained for candidates with and without perturbations, the student can quantify the extent to which deviations from strict periodicity influence the likelihood of a candidate being a genuine exoplanet.

Supervisors: Judith Korth (judith.korth@fysik.lu.se) and Alexander Mustill (alexander.mustill@fysik.lu.se)

References:

- Giacalone S., et al., 2021, Vetting of 384 TESS Objects of Interest with TRICERATOPS and Statistical Validation of 12 Planet Candidates., AJ, 161, 24. doi:10.3847/1538-3881/abc6af
- TRICERATOPS: https://triceratops.readthedocs.io/en/latest/index.html

9 Search for white dwarf binaries in the OGLE data

Background: White dwarfs are the end products of the evolution of low-mass stars. Binary white dwarfs are particularly interesting from the evolutionary point of view. They can also become cataclysmic variables, type Ia supernovae, super soft X-ray sources or gravitational wave sources. The search for white dwarf binaries is challenging due to their small size and faintness. However, large-scale photometric surveys, such as OGLE, provide an opportunity to greatly increase the number of detected white binaries.

Aims: The goal of this project is to search for white dwarf binaries within the OGLE catalog of eclipsing binaries towards the Galactic bulge, containing over 450 000 objects. We expect to find between tens and hundreds of new white dwarf binaries, which will significantly increase the known sample of such objects. You will look for the white dwarf binaries using the combination of OGLE and Gaia data. You will also perform a statistical analysis of the sample as a whole and try to identify particularly interesting systems (e.g. candidates for white dwarfs with transiting planets) that can be analyzed individually.

Methods: You will use the publicly available data including time-series photometry from the OGLE surveys and astrometry from Gaia, as well as tools appropriate for handling large datasets.

Supervisors: Michal Pawlak (michal.pawlak@fysik.lu.se) and Ross Church (ross@astro.lu.se)

10 The future of double clusters

Background: Most stars – probably, in fact, all stars – in our Milky Way galaxy form in groups. Some of these groups, representing perhaps 10% of star formation, survive their early dynamical evolution and expulsion of residual gas to become gravitationally bound open clusters, which survive up to a few Gyrs in the disk of the Galaxy. Open clusters are mostly isolated objects, with one well-known exception: the double cluster of NGC 869 and NGC 884. Data from Gaia has enabled many more open clusters to be discovered and existing clusters to be better characterised, and a recent paper (Song et al. 2022) reports the discovery of around 14 binary open clusters (including the double cluster).

Aims: In this project you will investigate the future of double open clusters. Some questions that you might attempt to answer: Will binary clusters dissipate individually into the Galactic disc, or will they merge? How does the answer to that question depend on their internal velocity dispersions, relative velocities, and birth environments? Can we distinguish merged binary clusters from single clusters using kinematic properties? How are the answers to these questions affected by the presence of binary stars in the clusters?

Methods: This is a theoretical / computational project. You will write some code to set up initial conditions for binary cluster systems, and use the NBODY6 software package to simulate their subsequent dynamical evolution. Cluster properties will be based on observed single and binary clusters in catalogues produced from Gaia data. Analysis of the simulations, plots, etc will be produced using your own code in Python.

Supervisor: Ross Church (ross@astro.lu.se)

References:

- Song et al. (2022) *Binary open clusters in the Gaia data. A&A* **666** 75. https://ui.adsabs.harvard.edu/abs/2022A%26A...666A..75S/abstract.