Institute of Astronomy
University of Cambridge

Natural Sciences Tripos
Part III/MASt Astrophysics

Research Project

2023-24

Contents

Part I: Key Information

Key Dates

Type	Milestone	When?		Format	Length	Where?
		Time	Date			
Submission	Interim Progress Report	12:00 noon	Last day of Full Michaelmas Term	PDF - LaTeX/equivalent	1,000 words	Moodle
Submission	Practice Presentation	12:00 noon	Last Monday of Lent Term	Microsoft PowerPoint /PDF	N/A	Moodle
Oral	Practice Oral Presentation	TBC	Last Tue. – Fri. of Lent Term	N/A	30 minutes	Hoyle Committee Room
Submission	Draft Final Report to Supervisor I	N/A	Last day of the Easter Vacation	PDF - LaTeX/equivalent	30 pages	Various
Submission	Final Report	12:00 noon	2nd Monday of Full Easter Term	PDF - LaTeX/equivalent	30 pages	Moodle
	Oral Presentation Slides			Microsoft PowerPoint /PDF	N/A	
Oral	Oral Presentation	TBC	2nd Tue. – Fri. of Easter Term	N/A	30 minutes	Hoyle Committee Room

The Part III/MASt Calendar

We **strongly advise** adding this calendar to your own, as it will be updated throughout the year with important events, deadlines and more.

- To add to an existing Google Calendar, click here.
- If you use another calendar, right click, copy and paste this link into your own calendar. Please note, simply clicking on the link will download a calendar file or import a copy directly into your calendar (depending on the software you use) but the information will not update as changes are made.

Format

The Written Report

Formal Requirements

- The Interim Report must not exceed 1,000 words in length
- The Final Report must not exceed 30 pages in length, including The Abstract, Figures, Tables, References, and Appendices (where applicable)
- The minimum acceptable font size is 11pt with at least single line spacing
- The text must be in single column format
- Margins must not be less than 2cm
- Figures must be legible when printed on A4 paper

Projects not meeting these requirements will be returned for revision and a penalty may apply for late submission at the discretion of the examiners.

Content

The Interim Progress Report

The Interim Progress Report, which may contain material that can be incorporated in the final project report, must indicate the progress made so far and show preliminary results. It should also give a clear indication of the project aims and a detailed plan of how these aims will be achieved. This is particularly important where the results of the project depend on data that has yet to be analysed.

There is no need for the Interim Progress Report to reiterate the material given in the Project Description.

The Final Report

The Final Report should read as a self-contained document, presented in the style of a scientific research report or paper in a scientific journal. The main sections of the report will describe the work undertaken, the results obtained and an assessment of their significance.

An Abstract, Introduction, Conclusions and References should also be included. Supporting Figures and Tables should be used both as an aid in presenting data and results and also to enhance the clarity of the submission. In some circumstances an appendix containing more extensive tabular material/results may be included.

The reader should be able to understand the context in which the investigation was undertaken, the main features of the project, the results and how they relate to the advancement of the subject. In addition to the descriptive material, questions a report would be expected to address include, "Why were particular approaches adopted?" – back of the envelope calculations will often be helpful and relevant – "What has been learnt?" and "What information/work would have helped us to learn more?" You should take care to demonstrate that you have tested any analysis packages/codes that you use.

Structure

You will have read many research papers in the course of your project research. Some of these you will have found easy to read and others less so. You therefore already have a good idea of what makes a good write-up.

The Final Report should be logically structured, clear, and complete, while remaining concise. It is usual to set out the write-up in sections that include an introduction, a description of methods, results, and conclusions. The introduction should set out the problem to be solved, including why it is interesting, and previous work done. The methods section should describe what you have done in sufficient detail that the work can be reproduced by a reader. It is important to make clear what new work you have done yourself in this section. In the results section describe what you have found. Try to make it very clear which are the most interesting outcomes of the project. In the conclusion explain whether or not you have solved the problem you set out to solve. If so, explain how and if not then why not. You can also describe future work that might get closer to or verify your solution.

There are some points to particularly bear in mind:

1. Remember that your readers may not be experts in the field of your project. Begin your description from basic physical principles and describe how any observations have been made.
2. Write short sentences. Long and convoluted sentences, with numerous sub-clauses, are hard to read and often grammatically incorrect.
3. Use named references, such as (Eggleton, Fitchett and Tout 1989), in the text. This is the style generally used by astronomers. It is much easier to read than a number reference style that requires continual cross-referencing.
4. Be concise. Well-written reports do not need to fill the page limit.
5. Include a limited number of pertinent figures. A good figure can replace many words, but many similar figures can often be replaced by a few words. Ensure that axes are labelled properly, lines are sufficiently thick, that points and labels are in a large enough font and that the main details of the figure are explained in the caption. Avoid making figures too cluttered and do not include anything that is not relevant to your discussion.
6. Appendices are for additional reading only. The examiners will base their marking on the main report.

The Oral Presentation

Formal Requirements

- The Oral Presentation must consist of a 20-minute description of the project followed by up to 10 minutes of questions from the Part III/MASt Examiners.
- The written presentation must be submitted as either a Microsoft PowerPoint (.pptx) or PDF file.

Referencing and Plagiarism

It is a requirement that the project investigation and the project report are both the work of the candidate alone and no form of collaboration is allowed.

It is a fundamental tenet of scientific research that due acknowledgment is given to the work and ideas of others that form the basis of, or are incorporated in, a research presentation. You must always acknowledge the source of an idea or material you use with a specific reference. Plagiarism, including the use of another individual's ideas, data, or text, is regarded as an extremely serious disciplinary offence by the University. For further information, please see the University's guidelines on Plagiarism and Academic Misconduct.

Assessment

The research project element of the NST Part III Astrophysics course accounts for 6 assessment units (equivalent to the marks assigned to two 24-lecture Mathematics Part III lecture courses).

Distribution of Marks

The Interim Progress Report

The Interim Progress Report does not constitute part of the formal assessment but is regarded as an essential part of the monitoring procedure. The Course Coordinator will assess these reports and provide feedback to students and supervisors.

The Mock Oral Presentation

This practice presentation, delivered to an audience including the Part III/MASt Course Coordinator, Project Supervisors and UTOs, is not formally assessed but offers the opportunity to become familiar with the format of the presentation to be assessed by the Part III/MASt Examiners in the Easter Term. Students are strongly encouraged to attend the practice talks of their peers to further develop their understanding of and exposure to various presentation techniques.

The Final Draft Report

The Final Draft Report does not constitute part of the formal assessment but provides students with an opportunity for their work to be read by their Primary Project Supervisor, who will provide feedback during the final supervision.

The Final Report

The research project written report counts for 5 out of the total of 6 units of assessment assigned to the research project i.e., approximately 85% of the marks for the research project will be assigned on the basis of the written final report.

The Final Oral Presentation

The research project oral presentation counts for 1 out of the total of 6 units of assessment assigned to the research project i.e., approximately 15% of the marks for the research project will be assigned on the basis of the assessed oral presentation.

Examiners Criteria for Marking the Project Report and Oral Presentation

The Examiners will award marks under three broad headings:

i. Scientific understanding
ii. Quality of the research
iii. Presentational and communication skills.

The format and timetable for submission form part of the Examination process. In their assessment of the project, the Examiners will take account of any breaches of the guidelines, including exceeding the word limit and late submission of the report.

Oral Presentation

The Examiners assessment will take into account the following:

- Visual Material: including relevance, clarity, attractiveness
- Oral Presentation: including overall structure, clarity, time keeping
- Response to Questions: including grasp of subject material, precision of answers

Written Project Report

The Examiners will assess the report under the following headings:

- Overall structure and clarity of the report
- Planning, organisation, and prosecution of the research
- Understanding of the physics and the general scientific content
- Technical proficiency
- Analytical and Interpretational skills
- Significance of the results

Extension Requests and Illness

The Institute of Astronomy expects students to meet the advertised deadlines for the submission of all coursework, to ensure fairness to all students taking the course and allow prompt marking by the Department.

Your Part III Project makes up one third of total available Tripos marks and is subject to special arrangements.

The Final Report and Final Presentation Slides are linked with compulsory attendance at the Final Oral Presentation, as such, it is not possible for the Department to grant an extension of more than 48 hours. The following policy builds around point 7 of the University's Dissertation and Coursework extensions policy.

Extension Requests for the Final Report and/or Final Presentation Slides of up to 48 hours

The student **must** apply to the Part III/MASt Course Coordinator via this form for an extension of up to 48 hours from the original deadline.

Requests must be submitted **no later than 7 days before the deadline** to allow for potential amendments to be made to the Final Oral Presentation schedule, Late submissions must then be submitted via email to the Undergraduate Student Coordinator via your college Tutor.

Extension Requests for the Final Report and/or Final Presentation Slides of over 48 hours

Late submission of over 48 hours is a particularly serious matter, and will require your College to apply to the Examination Access and Mitigation Committee (EAMC) to seek permission for any credit to be allowed. If this is not granted, the late work will not be counted.

The College **must** apply to the Secretary of the EAMC for an extension to a deadline and should **not** approach the Chair, Course Coordinator or Senior Examiner directly.

Applications must be submitted **no later than 7 days before the deadline** to enable the Secretary to consult the relevant Chair of Examiners or, where applicable, the Senior Examiner.

Illness during the Oral Presentations

The department defers to University Policy with regards to illness during an examination, including the Final Oral Presentation.

For full details, see the document entitled *All student guide to examinations* here.

Part II: The Project Descriptions

It is my pleasure to present the Research Project Booklet for the academic year 2023-2024, made possible thanks to generous and enthusiastic contributions of the Cambridge Astronomers.

Each of the projects on offer this year is only described briefly, but combined together these will add up to a lot of information-rich and often rather technical text to digest. I encourage you to take your time and use the month of September before the start of term to read carefully through the project descriptions, taking advantage of the references provided.

If you are interested in a project, please email the supervisors with your questions. It will also give the supervisors a chance to identify the most interested students. Many supervisors will also organise meetings with the students who have expressed interest, be it in person or remotely.

As usual, there are more projects on offer than there are students in the cohort, and the entire spectrum of the Cambridge Astronomy research is represented, so everyone should be able to find a project that interests and suits them the best. However, because the student-project ratio is not too far off unity and because typically the cohort's preferences tend to cluster around particular projects, please do not expect to be necessarily allocated your top choice.

To make it work, I will ask you to submit a ranked list with your top ten projects in October, at the beginning of the Michaelmas term. Supervisors will also be invited to express their preference of student if they wish to do so. Student and supervisor preferences will then be fed into a complex computer code which is designed to maximise overall satisfaction (with high weight assigned to student satisfaction). The project allocations will be announced a week after the preferences are collected.

Based on experience, my inkling is that there is more than just one project that would work great for you, but how to find them? Most importantly: be open-minded. This is your chance to learn first-hand what cutting-edge astrophysics is like. Pay less attention to the flavour/topic of research and more to the type of work involved. Projects involving the early Universe, exoplanets, black holes, stars, galaxies, dust and high energy particles will all have something in common: you will be asked to run simulations, analyse data and apply statistics to interpret your results. The absolute majority of our projects require familiarity with at least one programming language - most likely it will be Python, sometimes C/C++.

Singling out one particular project based on a set of fine-grain selection criteria is not a wise strategy, and such considerations will be impossible to satisfy given that the student-project ratio is close to unity. Instead use coarse-grain selection criteria to identify multiple projects you would be excited about, projects that will give you a chance to learn something new.

Please feel free to email me if you have any questions.

Vasily Belokurov, Part III/MASt Astrophysics Course Coordinator, Michaelmas term 2023
Email: vasily@ast.cam.ac.uk

List of Projects

Project 1: It's all in the dust: determining the mineralogy of dust accreting onto white dwarfs

Supervisor I: Amy Bonsor (abonsor@ast.cam.ac.uk)

UTO: Oliver Shorttle (shorttle@ast.cam.ac.uk)

Project Summary

White dwarf planetary systems provide a unique way to probe what exoplanets are made from. This project will focus on six white dwarfs with Spitzer/IRS spectra from the accretion of dusty material onto the star. The aim is to compare the mineralogy of the dusty material, as seen in the spectra, to the bulk composition of the material accreted by the white dwarf, as seen in the stellar photosphere.

Background

Almost all observed exoplanets orbit stars that will one day end their lives as white dwarfs. Whilst the inner regions of these planetary systems can be lost during the giant branch evolution, the outer planetary system should survive and orbit the white dwarfs (Veras 2016). Such outer planetary systems can continue to evolve dynamically, with occasionally asteroids or comets being scattered into the inner system (Debes & Siggurdsson 2002). Any body that approaches within a solar radius of the white dwarf is torn to pieces by the strong tidal forces and accreted onto the white dwarf (Debes 2012, Veras 2014). Photospheric metals from these planetary materials are seen in the white dwarf atmospheres, whilst infrared observations probe the dusty material accreting on to the white dwarf. Metals such as C, O, Mg, Ca, Cr, Ni seen in the white dwarf photosphere provide some of the best constraints available on the bulk composition of exoplanetary material (Jura 2014). Detailed spectra of the dust disc show emission features from e.g., silicate grains (as seen in Fig. 1) whose shape is controlled by the exact mineralogy of the grains.

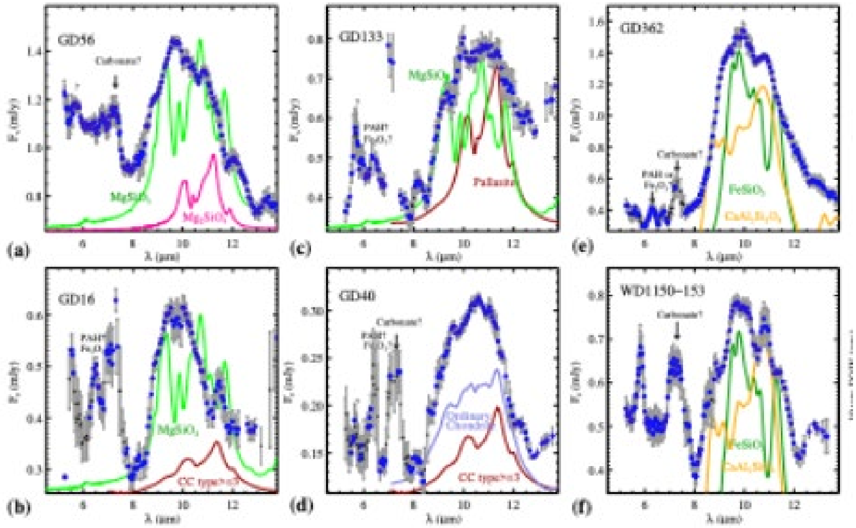

Figure 1.:Spitzer/IRS spectra of six dusty white dwarfs. The near-infrared spectra exhibit peaky emission from crystalline grains, whose form depends on the composition of the dusty material. These dusty white dwarfs will be the reference set for this project. (Su et al, private communication).

Project Details

The main aim of the project is to link the infrared dusty emission from six white dwarfs observed with Spitzer IRS to the composition of the accreted planetary material seen in the white dwarf photosphere.

The bulk composition determines the exact minerals that form in planetary bodies, be that as the first grains grow in the planet-forming disc or deep in the interiors of asteroids or planets. For example, for low Mg/Si, the mineralogy will be pyroxene dominated, whilst for higher Mg/Si the mineralogy will be olivine dominated.

This project will start by considering the bulk Mg and Si content of the material and how the near-infrared spectrum would change based on a lower Mg/Si (pyroxene dominated) or a higher Mg/Si (oliving dominated) composition. The final aim of the project is to use the photospheric abundances to predict the mineralogy of the dust by considering a Gibbs free energy minimisation (see Fig. 2 for example results). Following which, spectral libraries will be used to predict the emission features associated with different species to consider whether these are present in the observed spectra. The Gibbs free energy minimisation will be performed using an open-source code. The Spitzer IRS data is available from the Spitzer archive.

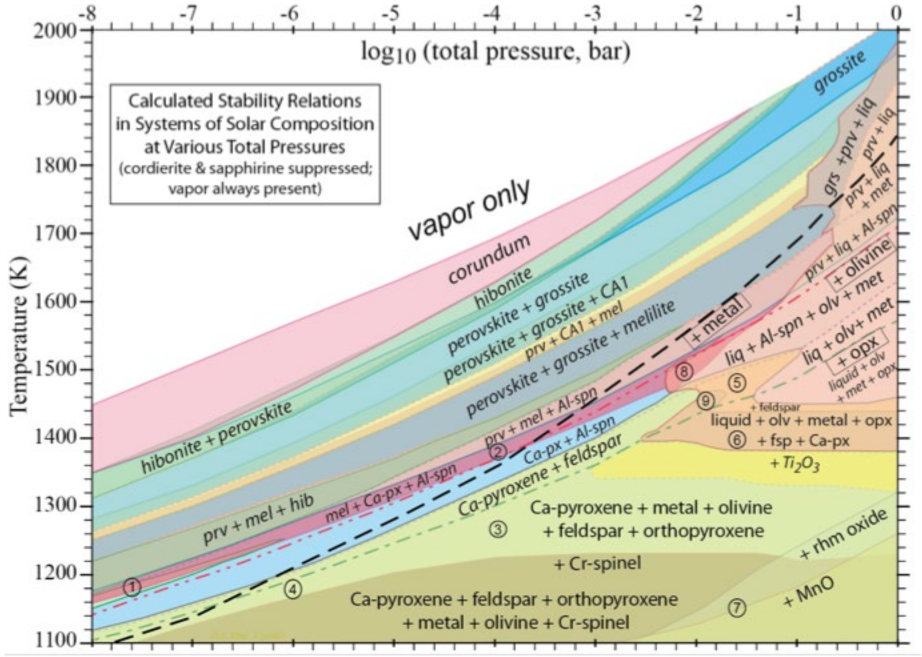

Figure 2.:The stability of various minerals in a gas of solar composition as a function of the pressure or temperature conditions experienced. The minerals present in the solid phase around a white dwarf will depend on the pressure, temperature conditions experienced, as well as the bulk composition. Diagrams such as above will be used to predict the near-infrared emission spectrum of a dusty white dwarf, based on various conditions. (Ebel et al, 2006)

Skills Required

- A desire to link observations to theoretical models.
- Basic python (or other) coding.
- Planetary Systems Dynamics and Exoplanets Part III courses (optional)

Useful References (List of important papers/review articles relevant to the project)

- Reach W.~T., Kuchner M.~J., von Hippel T., Burrows A., Mullally F., Kilic M., Winget D.~E.,2005,ApJL, 635,L161. Jura M., Farihi J., Zuckerman B., 2009, AJ, 137, 3191. doi:10.1088/0004-6256/137/2/3191. Xu S., Bonsor A., 2021, Eleme, 17, 241. doi:10.48550/arXiv.2108.08384

General References (List of papers referred to in the project)

- Ebel, D.S. (2006) Condensation of rocky material in astrophysical environments. In Meteorites and the Early Solar System II, (D. Lauretta, H.Y. McSween Jr., eds.) University of Arizona, Tucson. pp. 253-277.
- J. H. Debes and S. Sigurdsson, 2002, “Are There Unstable Planetary Systems around White Dwarfs?,” , vol. 572, pp. 556–565, doi: 10.1086/340291.
- D. Veras, 2016, “Post-main-sequence planetary system evolution,” Royal Society Open Science, vol. 3, p. 150571, Feb. 2016, doi: 10.1098/rsos.150571.
- D. Veras, Z. M. Leinhardt, A. Bonsor, and B. T. Gänsicke, 2014, “Formation of planetary debris discs around white dwarfs - I. Tidal disruption of an extremely eccentric asteroid,” , vol. 445, pp. 2244–2255, Dec. 2014, doi: 10.1093/mnras/stu1871.
- J. H. Debes, K. J. Walsh, and C. Stark, 2012, “The Link between Planetary Systems, Dusty White Dwarfs, and Metal-polluted White Dwarfs,” , vol. 747, p. 148, Mar. 2012, doi: 10.1088/0004-637X/747/2/148.
- M. Jura and E. D. Young, 2014, “Extrasolar Cosmochemistry,” Annual Review of Earth and Planetary Sciences, vol. 42, pp. 45–67, May 2014, doi: 10.1146/annurev-earth-060313-054740.

Project 2: Tracing the composition of exoplanets

Supervisor I: Laura Rogers (lr439@cam.ac.uk)

Supervisor II: Amy Bonsor (abonsor@ast.cam.ac.uk)

UTO: Mark Wyatt (wyatt@ast.cam.ac.uk)

Project Summary

This project focuses on a novel means to probe the composition of exoplanetary material using emission from gaseous planetary material accreting onto white dwarfs. By modelling emission from species including Mg, Ca, and Fe and comparing these to the observations, this project aims to determine the bulk composition of the gas, starting from its Mg/Ca ratio. This bulk composition tells us what the original exoplanetary bodies were like when they once orbited a main-sequence star, long before being disrupted and accreted onto a white dwarf. Planetary material is detected interior to the white dwarf atmosphere. By comparing the abundances of the material accreting onto the star with the accreting gas, this project will probe the timescales for accretion in white dwarf planetary systems.

Background

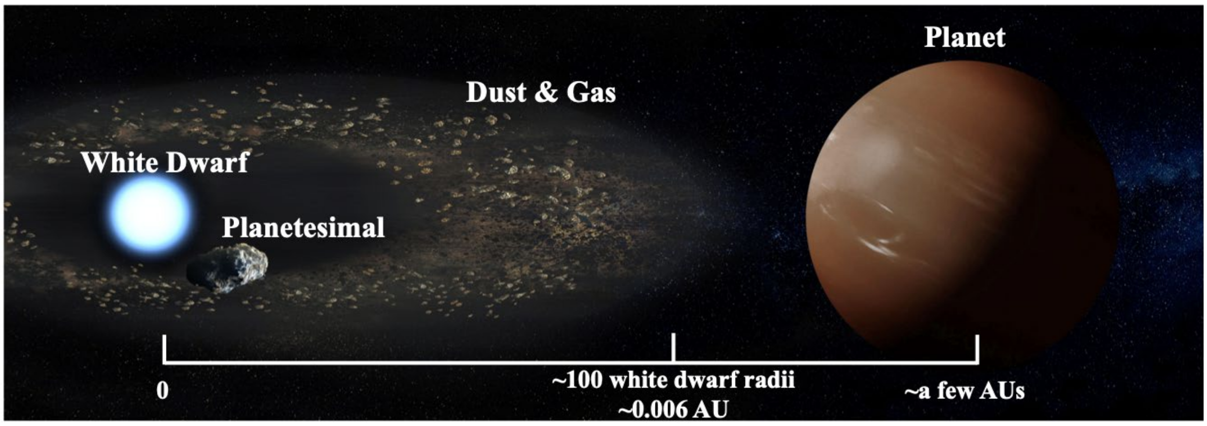

Figure 1.:A cartoon illustrating the arrival of planetary material onto white dwarfs. Crucial to this project is the gas accreting onto the star and the planetary material seen in the atmosphere of the white dwarf (Xu & Bonsor, 2021)

As we detect more and more exoplanets around other stars, we would like to find out more about these planets, crucially what conditions might be like on the surface and whether they may indeed be habitable. In order to determine these properties, it is key to know what a planet is made from. However, with only a mass and radius measurement for most known exoplanets this is hard.

White dwarf planetary systems provide unique constraints on the bulk composition of planetary material (Jura & Young, 2014). This planetary material is either seen in their otherwise pure H/He atmospheres or in emission features from the vaporized planetary material accreting onto the white dwarf. Outer planetary systems are thought to survive the star's evolution to the giant branch, with occasional asteroids or comets being scattered close to the white dwarf. These planetary bodies are torn apart by the strong gravity of the white dwarf and accrete onto the star (see Veras et al, 2016 for a review). Planetary material has now been seen in the atmospheres of more than ~1,000 white dwarfs, whilst emission from gaseous material is seen accreting onto over a dozen white dwarfs.

Emission from Ca, Mg, O etc in the gaseous material are observed, with profiles that are consistent with Keplerian rotation in potentially eccentric gas discs (e.g., Gänsicke et al, 2006, Manser et al, 2016, Dennihy et al, 2020). This gas is thought to originate from the disruption of asteroids or comets, as they accrete onto the star. Rocky material reaches sufficiently high temperatures to sublimate before reaching the white dwarf surface. The gas may potentially spread viscously outwards from the inner disc around the white dwarf (Rafikov) .

Project Details

The aim of the project is to determine the composition of the gas seen in emission accreting onto a number of white dwarfs. Not only do these observations alone provide a unique way to probe the composition of exoplanetary material, but comparison with the composition seen in the stellar photosphere tells us about the timescales for accretion. Does the planetary material accrete onto the white dwarf on the same timescales regardless of its volatility?

The radiative transfer code Cloudy will be used to model the emission from metallic gas orbiting close to the white dwarf. By considering a 'slab' of gas heated by a white dwarf, Cloudy will predict the spectrum of the gas. The range of emission features will differ depending on the composition of the gas (as well as other parameters). By comparing the relative strength of features in the observed spectra to those predicted by Cloudy, this project will constrain the composition of the gas.

The project will firstly consider Mg/Ca as a key tracer observed in both the accreting gas and see in the white dwarf photospheres (see Fig. 2, 3.). The project will use existing code base for basic Cloudy models of white dwarf gas discs. The gas is likely at thousands of kelvin with a high metallicity (and no/little hydrogen).

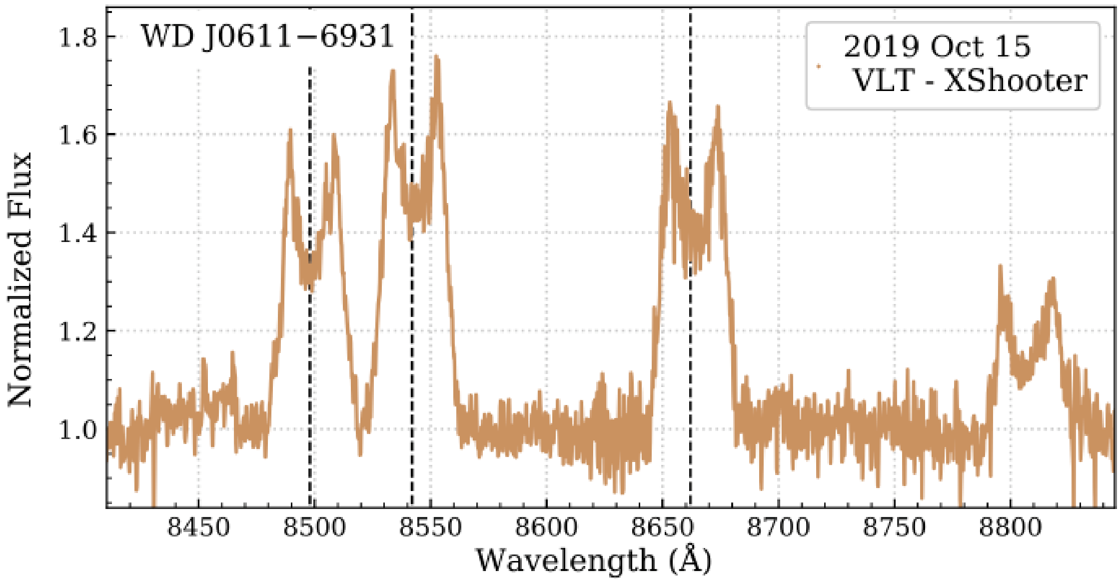

Figure 2.: Emission from gaseous material accreting onto the white dwarf WD J0611. The three peaks on the left result from the calcium triple, whilst the features seen at 8806angstrom is from Mg. (Dennihy et al, 2020)

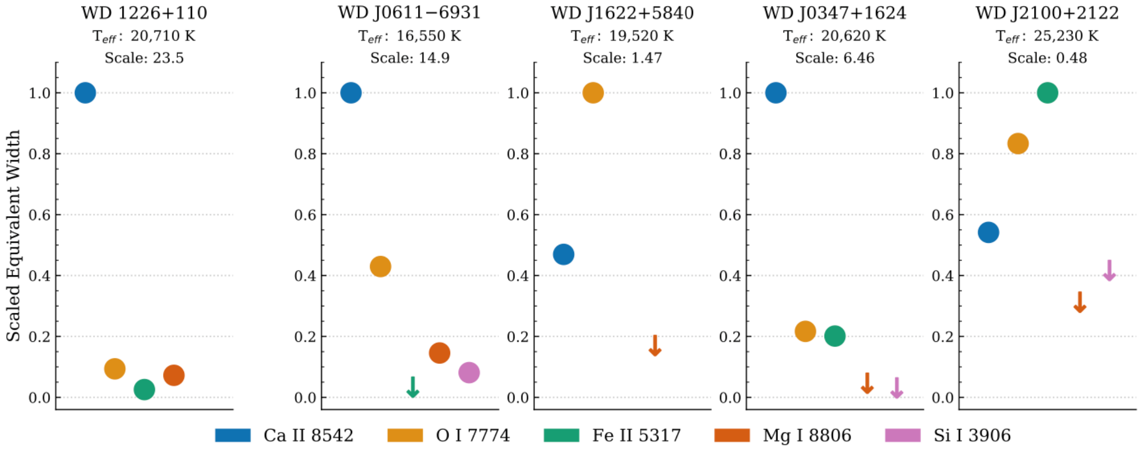

Figure 3.:The relative strength of emission features from various elements seen in the gas accreting onto five white dwarfs (Dennihy et al, 2020)

Skills Required

- Basic python (or other equivalent language) and experience with linux (or desire to learn) .
- Attendance of the Exoplanets and/or Planetary Systems Dynamics Part iii course would be useful, but not essential.

Useful References (List of important papers/review articles relevant to the project)

- Xu S., Bonsor A., 2021, Eleme, 17, 241. doi:10.48550/arXiv.2108.08384 Dennihy E., Xu S., Lai S., Bonsor A., Clemens J.~C., Dufour P., G{\"a}nsicke B.~T., et al., 2020, ApJ, 905, 5. doi:10.3847/1538-4357/abc339 https://arxiv.org/pdf/2010.03693.pdf
- A. Steele, J. Debes, S. Xu, S. Yeh, and P. Dufour, “A Characterization of the Circumstellar Gas of WD 1124-293 Using Cloudy,” , vol. 911, no. 1, Art. no. 1, Apr. 2021, doi: 10.3847/1538-4357/abc262.

General References (List of papers referred to in the project)

- Dennihy, Erik, et al. "Five new post-main-sequence debris disks with gaseous emission." The Astrophysical Journal905.1 (2020): 5.
- M. Jura and E. D. Young, 2014, “Extrasolar Cosmochemistry,” Annual Review of Earth and Planetary Sciences, vol. 42, pp. 45–67, May 2014, doi: 10.1146/annurev-earth-060313-054740.
- C. J. Manser et al.,2016, “Doppler imaging of the planetary debris disc at the white dwarf SDSS J122859.93+104032.9,” , vol. 455, pp. 4467–4478, Feb. 2016, doi: 10.1093/mnras/stv2603.
- B. T. Gänsicke, T. R. Marsh, J. Southworth, and A. Rebassa-Mansergas, “A Gaseous Metal Disk Around a White Dwarf,” Science, vol. 314, p. 1908–, Dec. 2006, doi: 10.1126/science.1135033.
- D. Veras, 2016, “Post-main-sequence planetary system evolution,” Royal Society Open Science, vol. 3, p. 150571, Feb. 2016, doi: 10.1098/rsos.150571.

Project 3: Probing the merging of the most massive supermassive black holes with Nano-Hz gravitational waves

Supervisor I: Martin Haehnelt (haehnelt@ast.cam.ac.uk)

Supervisor II: Vid Irsic (vi223@cam.ac.uk)

UTO: Martin Haehnelt (haehnelt@ast.cam.ac.uk)

Project Summary

The NanoGrav collaboration has recently announced the discovery of directional correlations in the previously reported excess noise in pulsar timing residuals which they interpret as being due to a stochastical gravitational wave background. The collaboration further presented the merging of supermassive black holes in galaxies as their favoured explanation for the origin of such a stochastical gravitational wave background. To this end the collaboration presents a simple model for calculating the amplitude this stochastical gravitational wave background as a function of gravitational wave frequency. In this project we will verify this simple model and scrutinize some of the underlying assumptions to better understand the implications for the co-evolution of galaxies and their central supermassive black holes.

Background

The standard Lambda-CDM paradigm of structure formation predicts that the more massive galaxies build-up hierarchical merging of smaller galaxies, a picture confirmed by a plethora of observations and intensively studied by numerical simulations with supercomputers (see Dodelson & Schmidt (2020) for a textbook on Cosmology). Supermassive black holes (SMBHs) at the centre of the galaxies are thereby by an essential ingredient of galaxies and are predicted to form supermassive black hole binaries when galaxies merge (see Haehnelt 1994 for simple predictions of SMBH formation rates). These SMBH binaries are expected to decrease in separation by a mixture of accretion of gas and interaction with the surrounding stars, a process which is called binary hardening. SMBH binaries that reach sub-pc separations in this way will harden further due to the emission of gravitational waves (see Begelman et al. 1980 for a discussion of SMBH hardening). The collective gravitational wave signal in the nano-Hz range from hardening SMBH binaries leads to a random jitter of positions of celestial objects. This will lead to excess "noise" in the arrival times of the observed signals from rotating neutron stars pulsed with extremely stable milli-second periods called millisecond pulsars (see Sesanna (2014) for a review of detecting gravitational waves from merging SMBHs with pulsar timing arrays). This excess noise is being monitored and has now been detected with the expected frequency dependency and directional correlations by the NANOgrav collaboration. If indeed due to hardening of SMBHS, amplitude and exact frequency dependency of the inferred gravitational wave strain encode important information on the hardening and the merging of the most massive SMBH binaries (NANOGrav Collaboration 2023).

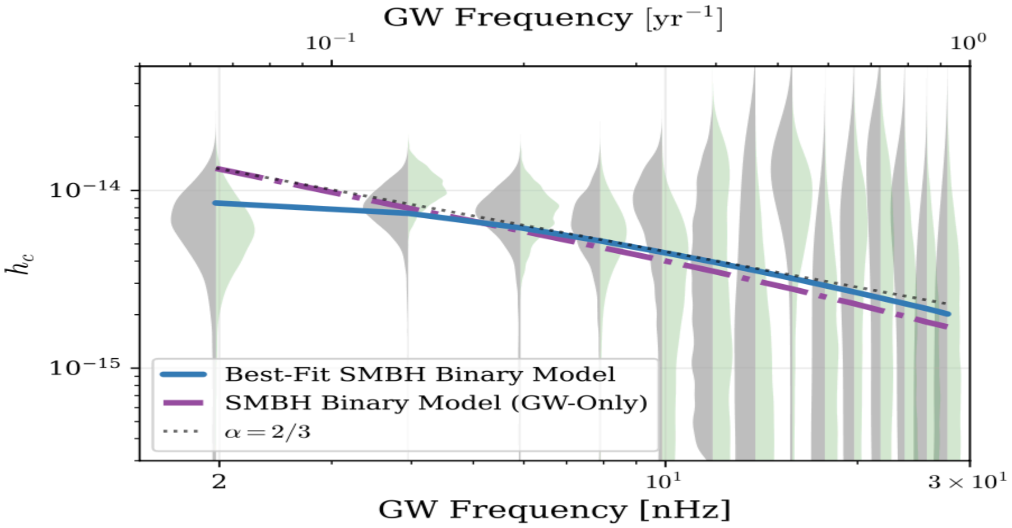

Fig. 1: Gravitational wave strain as a function of frequency derived from 15 years of pulsar timing residuals as reported by the NANOGrav collaboration. The inferred gravitational wave strain is shown with errors in gray and green with two different assumptions for the noise model. The dotted black curve shows the canonical α=2/3 power law. A model for SMBH binary hardening by gravitational waves only and a model where SMBH binaries hardening is assumed to be accelerated by astrophysical processes are shown by the purple dash-dotted and the solid blue curve, respectively.

Project Details

The project will involve:

1. Making estimates of the merger rates of black holes from observed scaling relations of supermassive black holes
2. Modelling the hardening of supermassive black hole binaries
3. Calculating the amplitude and frequency dependency of the resulting stochastical gravitational wave background in the nano-Hz range.

Skills Required

- The project will require programming in Python. Knowledge of C would be beneficial.
- (Some of) the content of the Part II courses "Physics of Astrophysics", "Stellar Dynamics and Structure of Galaxies", "Relativity" and "Introduction to Cosmology" should all be relevant.

Useful References (List of important papers/review articles relevant to the project)

- Sesana, A., 2014, https://arxiv.org/pdf/1407.5693.pdf
- NANOGrav Collaboration, 2023, https://arxiv.org/pdf/2306.16220.pdf, https://nanograv.org/15yr/Summary

General References (List of papers referred to in the project)

- Dodelson & Schmidt (2020), "Modern Cosmology", Amsterdam: Academic Press
- Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307
- Haehnelt, M.G., 1994, MNRAS, 269, 199

Project 4: Machine learning models for clusters of the first stars

Supervisor I: Boyuan Liu (bl527@cam.ac.uk)

Supervisor II: Stephanie Monty (sm2744@cam.ac.uk)

Supervisor III: Anastasia Fialkov (afialkov@ast.cam.ac.uk)

UTO: Anastasia Fialkov (afialkov@ast.cam.ac.uk)

Project Summary

The first stars in the Universe, the so-called Population III (Pop III) stars, are expected to be more massive and compact than present-day stars due to the special chemical composition of the early Universe. Recent (magneto)hydrodynamic simulations of Pop III star formation have converged on the picture that Pop III stars typically form in small clusters of a few to a few tens of members where binary and multiple systems are common (Klessen & Glover 2023). Given the massive and compact nature of Pop III stars, binaries of Pop III stars are promising progenitors of X-ray binaries (XRBs, Sartorio et al. 2023) and binary black hole (BBH) mergers (Santoliquido et al. 2023). The former drive the thermal and ionisation evolution of the intergalactic medium in the early Universe, while the latter are loud gravitational wave sources. Therefore, robust modelling of Pop III star clusters, especially for the properties of binary/multiple systems within them, is necessary to understand signals from the early Universe in both the electromagnetic and gravitational wave windows.

Due to the chaotic nature of star cluster evolution, a large set of star clusters needs to be simulated to obtain reliable statistics of binaries/multiples. Ideally, one should first run (magneto)hydrodynamic simulations of Pop III star-forming clouds to obtain newly born Pop III star clusters, and then evolve these clusters with gravitational N-body simulations to derive the binary/multiple statistics. Although the second step is straightforward, the first step is computationally prohibitive for a large set of simulations. An approach to solving this problem is to use generative models, which are commonly used in machine learning. One can train generative models to randomly generate new sets of star clusters from a given representative set of clusters produced by (magneto)hydrodynamic simulations and provide abundant samples of initial conditions for N-body simulations. This idea has been applied to clusters of present-day stars by Torniamenti et al. (2022). In this project, the student will build generative models for Pop III star clusters from the outputs of state-of-the art (magneto)hydrodynamic simulations of Pop III star formation (Sharda et al. 2020). An ambitious student may wish to further run N-body simulations of large samples of generated star clusters to make novel predictions on Pop III binary statistics (see e.g., Liu et al. 2021) (see e.g., Liu et al. 2021) as well as the corresponding populations of XRBs and BBH mergers.

Background

In the standard picture of Pop III star formation (Figure 1), we start at a collapsing cloud of a few thousand solar masses in a small dark matter halo of a few million solar masses (Phase 0). After the initial collapse, a protostellar disk forms at the centre. The disk is unstable and undergoes fragmentation to produce protostars that grow by accretion and mergers, until eventually gas inflows are turned off by the radiation from protostars (Phase 1). Thereafter, we have a newly born Pop III star cluster whose evolution is governed by N-body dynamics and stellar evolution (Phase 2).

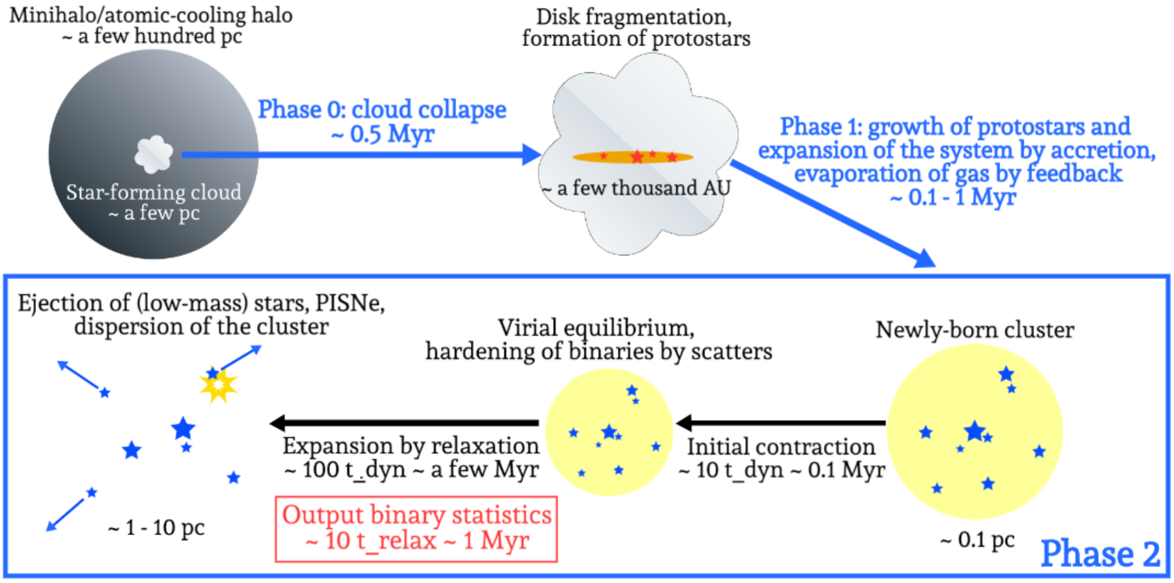

Figure 1: Illustration of the standard picture of Pop III star formation. From fig. 1 in Liu et al. (2021). In this project, the student will build generative models for newly born Pop III star clusters as the outcomes of Phase 1 and initial conditions for Phase 2. We can further run N-body simulations of the generated clusters in Phase 2 to predict the binary statistics of Pop III stars.

With limited computational power, current 3D (magneto)hydrodynamic simulations of Pop III star-forming clouds cannot follow the detailed evolution from initial protostar formation to well-defined star clusters, but this missing piece of information is crucial for binary/multiple properties. Nevertheless, two trends have been learned from current simulations (Susa 2019; Sugimura 2020, 2023; Park et al. 2023a, b): (1) The distances between Pop III protostars tend increase as their masses grow by accretion of infalling gas with high angular momentum. (2) Pop III protostellar disks undergo hierarchical fragmentation (Figure 2), such that new fragments form in the sub-disks of individual pre-existing fragments/protostars. Given these two trends, Liu et al. (2021) build a phenomenological model to fill the gap in hydrodynamic simulations and generate newly born Pop III star clusters, which are then evolved with N-body simulations. They find that assumptions on initial cluster properties have a strong impact on the binary statistics of Pop III stars (Figure 3). While their simple phenomenological model is useful to explore the parameter space, it may not fully capture the internal structure of Pop III (proto)star clusters. Besides, magnetic fields are not considered in Liu et al. (2021). Considering this, we plan to train generative models on the recent (magneto)hydrodynamic simulations of Pop III star-forming clouds by Sharda et al. (2020) to better capture the internal structure of Pop III (proto)star clusters during and towards the end of Phase 1 evolution under different strengths of magnetic fields. The generative models will then be combined with the trend of expansion during mass growth to generate newly born Pop III star clusters as initial conditions for N-body simulations of Phase 2 evolution.

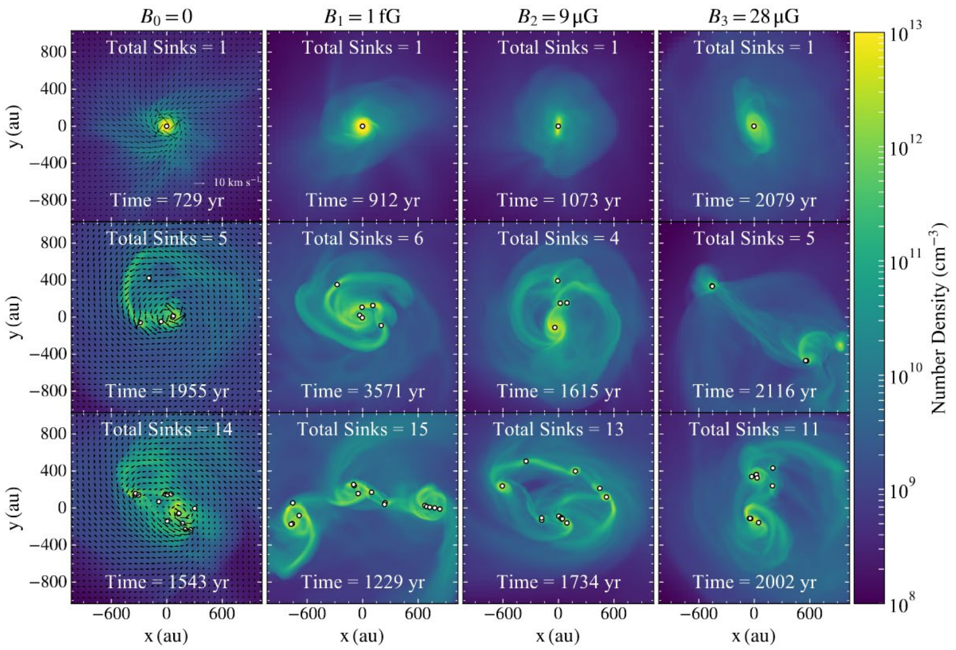

Figure 2. Density-weighted projection maps (through the z axis) of the number density of three simulations of Pop III star formation from each of the four cases with different initial magnetic strengths in each column. These realisations depict the central 0.01 pc region and result in no, medium and high fragmentation, respectively (from top to bottom). The maps correspond to a time when all the sink particles (white circles with black boundaries, representing protostars) have collectively accreted 5 percent of the initial cloud mass to reach a total mass of 50 solar masses. Time in the panels is given as time since the formation of the first sink particle. The contours on the first column depict the velocity vectors of the gas in the x − y plane. Signature of hierarchical fragmentation can be seen in the bottom two rows. From fig. 1 in Sharda et al. (2020).

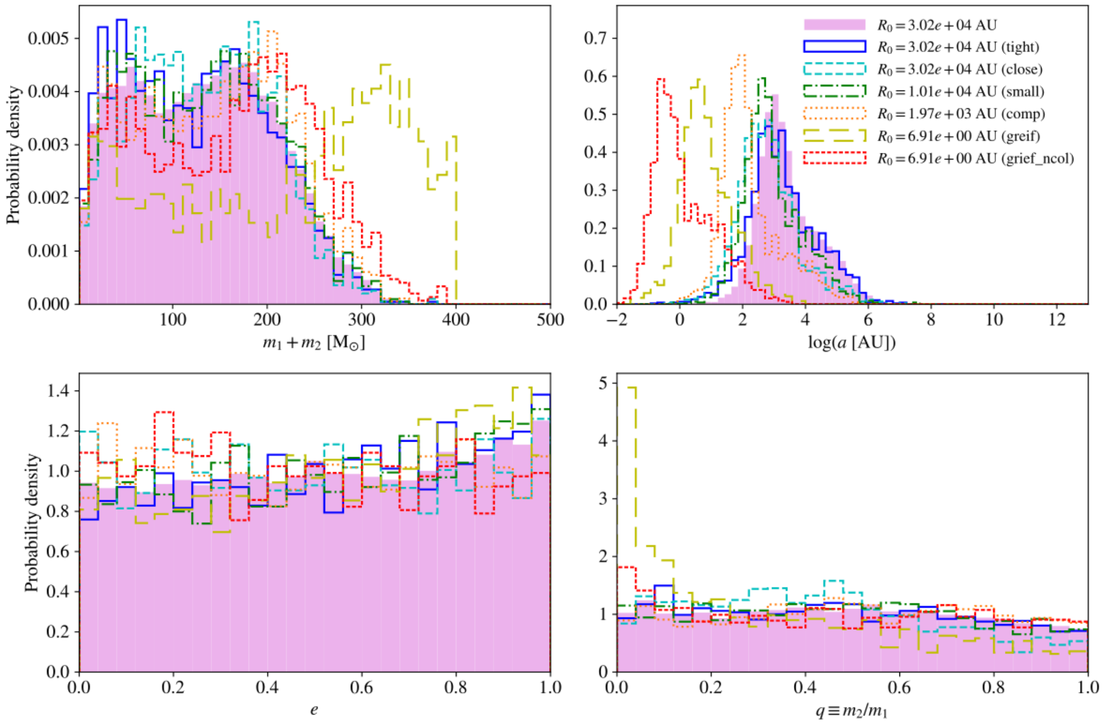

Figure 3. Binary statistics of Pop III stars from seven models of star clusters with different initial cluster sizes, internal structure, and stellar collision schemes, in terms of the distributions of total mass, semimajor axis (separation), secondary to primary mass ratio and orbital eccentricity (clockwise). From fig. 13 in Liu et al. (2021).

Project Details

1. Literature review on the formation and basic properties of the first stars (Klessen & Glover 2023).
2. Analyse the phase space distributions of protostars in the (magneto)hydrodynamic simulations of Pop III star formation by Sharda et al. (2020), see Sec. 2.2 in Torniamenti et al. (2022).
3. Arrange the protostars from each simulation into a tree-like structure in phase space with hierarchical clustering algorithms, see Sec. 3.1 and 3.2 in Torniamenti et al. (2022). https://scikit-learn.org/stable/modules/clustering.htmlUseful tools are available in the python package SCIKIT-LEARN library.
4. Build generative models based on phase-space hierarchical clustering for Pop III protostars from the simulation data under different strengths of magnetic fields, see Sec. 3.3 in Torniamenti et al. 2022.
5. Generate large sets of Pop III protostar systems, calculate the corresponding binary/multiple statistics of protostars and compare them with those from (magneto)hydrodynamic simulations to evaluate the performance of the generative models.
6. Implement mass growth and expansion in the generative models to generate large sets of newly born Pop III star clusters, using the general trends for (early) Phase 1 evolution described in Liu et al. (2021) and results of recent radiative hydrodynamic simulations of Pop III star formation from Park et al. (2023a, b).
7. Calculate the binary/multiple statistics of stars in the generated star clusters and compare them with the results for Pop III protostars and present-day stars.
8. (optional) Run N-body simulations of the generated Pop III star clusters to predict the binary/multiple statistics at cluster dispersion (see Liu et al. 2021). We can use public N-body codes such as nbody6 and ph4 in the AMUSE framework.

Skills Required

- Programming in python
- Knowledge of star formation and gravitational N-body dynamics of collisional systems (covered by Part II courses “Stellar Dynamics and Structure of Galaxies” and “Topics in Astrophysics”) would be useful but NOT necessary.

Useful References (List of important papers/review articles relevant to the project)

- Torniamenti et al. 2022, Hierarchical generative models for star clusters from hydrodynamical simulations, MNRAS, 510, 2097
- Sharda et al. 2020, The importance of magnetic fields for the initial mass function of the first stars, MNRAS, 497, 336
- Liu et al. 2021, Dynamical evolution of population III stellar systems and the resulting binary statistics, MNRAS, 501, 643
- Klessen & Clover 2023, The first stars: formation, properties, and impact, arXiv:2303.12500

General References (List of papers referred to in the project description)

- Susa 2019, Merge or survive: number of Population III stars per minihalo, ApJ, 877,99
- Sugimura et al. 2020, The birth of a massive first-star binary, ApJ, 892, L14
- Sugimura et al. 2023, Formation of massive and wide first-star binaries in radiation hydrodynamics simulations, arXiv:2307.15108
- Park et al. 2023a, Population III star formation in an X-ray background: III. Periodic radiative feedback and luminosity induced by elliptical orbits, MNRAS, 521, 5334
- Park et al. 2023b, On the origin of outward migration of Population III stars, arXiv:2307.14562
- Santoliquido et al. 2023, Binary black hole mergers from population III stars: uncertainties from star formation and binary star properties, MNRAS, 524, 307
- Sartorio et al. 2023, Population III X-ray binaries and their impact on the early universe, MNRAS, 521, 4039

Project 5: Understanding Galaxy Populations and Their Evolution Through Machine Learning

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Project Summary

A renaissance is underway in our understanding of stellar populations in galaxies, complemented by an explosion of data on the evolution of galaxies through cosmic time from deep, wide-field spectroscopic and imaging surveys. In this project we will explore the application of unsupervised machine-learning approaches to disentangle the connection between the astrophysics of galaxy populations and observational data (spectra and broadband colours) with the aim of producing diagnostics of particular astrophysical processes that can be applied to large datasets.

In this project we will create compressed representations of simulated galaxy populations within a variational autoencoder framework and explore this compressed representation (latent space) through the use of an information-theoretic metric known as mutual information. By estimating mutual information between the latent variables and various properties of the data, we will quantify diagnostics critical to our understanding of the interconnected astrophysical processes through which galaxies evolve (Sedaghat+21, Piras+23, Chartab+23). This project will revisit key galaxy evolution trends such as the fundamental metallicity relation, and processes such as the UV/IR dust processing energy balance in this compressed latent space via mutual information. A stretch goal in the project is to explore and quantify the observational degeneracies between age, dust, and metallicity with this new machine-learning framework, designed for scalability to address the unprecedented size of modern survey datasets. This project is both timely and addresses a tangible need to expand our analysis toolkit for upcoming surveys such as Rubin Observatory's Legacy Survey of Space and Time (LSST).

Background

This project will operate at the intersection of galaxy formation & evolution physics and recent statistical analysis tools. The project will therefore heavily involve the use of computational techniques, together with a strong background of observational literature. On the astrophysics side, the student is expected to become familiar with well-studied concepts in galaxy evolution, inspecting the interplay between the stellar populations, gas and dust content. Jointly, the student will develop familiarity with stellar population synthesis (SPS) modeling. SPS is widely used in deriving the physical properties of stellar populations (galaxies, star clusters), such as their mass or metallicity, from observed spectral energy distributions (SEDs, Conroy 2013). We show example galaxy SEDs in Figure 1. The student will as a result gain familiarity with popular SPS frameworks such as Flexible Stellar Population Synthesis (FSPS).

A major part of this project will involve the implementation and/or application of machine learning (ML) techniques. The student will have the opportunity to gain hands-on experience in the development and use of especially unsupervised learning and representation learning techniques. To exemplify, the student will acquire a working knowledge of widely used frameworks such as variational autoencoders (VAE, Kingma & Welling 2019 for a review), which joins these two.

Finally, the project will utilise approaches from the information theory toolkit to interpret the (latent) representation assembled by the VAE. The student will therefore have the opportunity to learn about core concepts in information theory such as Shannon entropy, and mutual information. Mutual information measures the information conveyed by one variable about another, becoming zero if and only if the variables are independent. The aim in this approach is for the latent representation to capture core galaxy evolution diagnostics, and mutual information to form a quantitative link to physical properties.

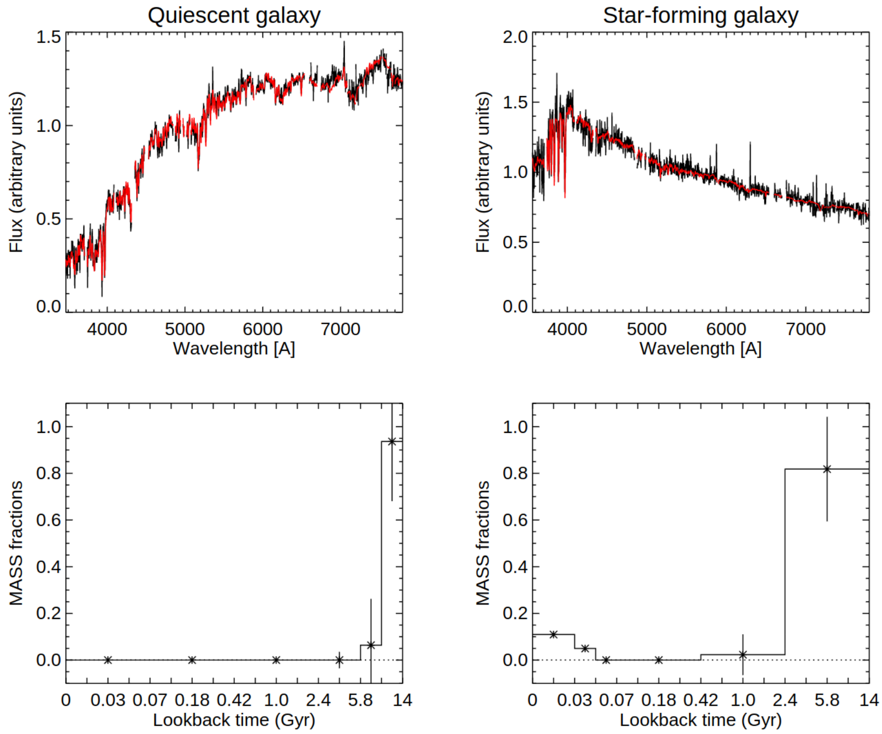

Figure 1: Observed SEDs of a quiescent (top left) and star-forming galaxy (top right) shown in black. The SEDs encode a wealth of information about the properties of galaxies. A best-fit model for the observations is overplotted in red in both panels. The bottom two panels show the fraction of mass contained in stellar populations at ages denoted as star-shaped markers in the best-fit models. The model for the quiescent galaxy has none of its total stellar mass in stars younger than 5 Gyr, whereas the star-forming galaxy has a non-negligible number of stars younger than 1 Gyr. Figure repurposed from Conroy (2013), Figure 9.

Project Details

The project will begin by building a library of galaxy SEDs representative of observed galaxy populations. Next, we will evaluate compressed representations of these galaxy SED's using VAEs. A demonstration of this is shown in Figure 2. This will involve various testing and validation stages, carefully analysing the reconstruction quality, the impact of disentanglement and similar.

A workflow can be summarised (but does not need to be limited to) the following:

- review of literature on the reference list and related papers,
- build / repurpose a library of synthetic galaxy SEDs,
- run VAE to build a compressed latent representation of this population,

- deploy GMM-MI (Piras+23) to measure mutual information between the compressed representation and physical properties.

As the project develops, the student will also have the opportunity to keep up to date with the latest developments in machine learning and astrophysics.

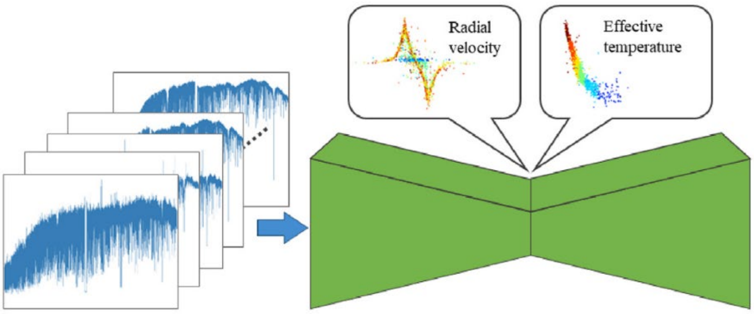

Figure 2: A demonstration of the technique proposed in this project. The green shape denotes the compression applied to inputs (stellar SEDs shown in blue) by the encoder, and the reconstruction from this compressed representation by the decoder. This figure is repurposed from Sedaghat et al. (2021), Figure 1, where the physical properties of interest in their paper were related to individual stars as shown in the bubbles above the compressed representation (or information bottleneck, as referred in the paper).

Skills Required

- The Part III Course *The Life and Death of Galaxies* is recommended.
- The project will heavily involve developing and making use of codes written in Python and Python-based machine learning libraries such as TensorFlow/Keras or PyTorch. Therefore, we expect interested students to have experience in programming with Python, and a keenness to build upon it during the course of the project.

Useful References (List of important papers/review articles relevant to the project)

- C. Conroy (2013) (https://arxiv.org/abs/1301.7095) – Review paper on galaxy SEDs
- Kingma & Welling, (2019) (https://arxiv.org/abs/1906.02691) – Review of VAEs
- Weaver et al. (2022) (https://arxiv.org/abs/2110.13923) – Example extragalactic survey, COSMOS2020

General References (List of papers referred to in the project)

- J. Alsing et al (2020) (https://arxiv.org/abs/1911.11778)
- J. Alsing et al. (2023) (https://arxiv.org/abs/1911.11778)
- B. Leistedt et al (2023) (https://arxiv.org/abs/2207.07673)
- N. Sedaghat et al. (2021) (https://arxiv.org/abs/2009.12872)
- D. Piras et al. (2023) (https://arxiv.org/abs/2211.00024)
- Melchior et al. (2023) (https://arxiv.org/abs/2211.07890)
- Y. Liang et al (2023) (https://arxiv.org/abs/2302.02496)
- N. Chartab et al. (2023) (https://arxiv.org/abs/2208.14781)

Project 6: Primordial B-mode polarization of the CMB and the “shadow effect”

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Project Summary

Our Universe appears to have evolved from very special initial conditions. Cosmic inflation – a brief period of quasi-exponential expansion in the early Universe – is a compelling mechanism for generating these initial conditions dynamically. Inflation naturally generates almost-scale-invariant primordial fluctuations in the density of matter, which are later imprinted as anisotropies in the cosmic microwave background (CMB) and subsequently grow under gravity to form the observed large-scale structure. If the Universe expanded rapidly enough during inflation, a primordial background of gravitational waves should also be produced. The best way to search for these ultra-long-wavelength gravitational waves is with a particular curl-like pattern – known as B-modes – in the linear polarization of the CMB. However, there are other sources of B-mode polarization in our observations that must be carefully removed to reveal any primordial signal. The most troublesome is polarized foreground emission from our Galaxy, including thermal emission from small dust grains aligned in the Galactic magnetic field. Many methods have been developed to remove Galactic foreground emission, typically exploiting its different frequency dependence compared to the primordial CMB signal. Recently, a potential new foreground has been identified, a “shadow effect” arising from the absorption of the background CMB light by these same dust grains. The frequency dependence of this absorption signal differs from those of dust emission and the CMB. The purpose of this project is to assess the impact of this new absorption signal on searches for B-mode polarization in the context of the Simons Observatory (SO), a new CMB observatory that will be operational later this year in Chile. Depending on the size of the signal, and if time allows, it may be necessary to explore cleaning approaches to mitigate the absorption signal using SO's multi-frequency capability.

Background

Cosmic inflation was introduced to resolve several puzzles of Big-Bang cosmology, such as why the universe is so close to being spatially flat and why the temperature of the cosmic microwave background (CMB) is so uniform. Arguably a greater triumph of inflation is that it naturally provides a causal mechanism for generating all structure in the universe. Quantum fluctuations on microscopic scales were stretched outside the Hubble radius during inflation, providing the primordial perturbations that seeded large-scale cosmic structures and the temperature anisotropies in the CMB. This same mechanism should also produce a primordial background of gravitational waves. If inflation occurred at high enough energies (around 10^16 GeV) this background should be detectable in the CMB.

The basic predictions of simple inflation models – a spatially flat universe with adiabatic, Gaussian-distributed primordial density perturbations with an almost, but not quite, scale-invariant power spectrum – have been verified to high accuracy with CMB temperature measurements (most notably from Planck). The one missing element is the detection of primordial gravitational waves. Detection of such a background would provide very compelling evidence that cosmic inflation did actually occur and would tell us the associated energy scale. Planck has reported tight constraints on gravitational waves based on the large-angle signature that they would leave in the temperature anisotropies. This route is limited, however, by confusion from the dominant density perturbations. Fortunately, the linear polarization of the CMB provides a way around this confusion since the curl-like B-mode polarization is not sourced by density perturbations at linear order (see Kamionkowski & Kovetz 2016 for a review).

The B-mode polarization signal from gravitational waves has not yet been detected. The measurement is very tricky since the amplitude is certain to be small and, at typical observing frequencies around 150 GHz, is sub-dominant compared to polarized emission from our Galaxy over nearly all the sky. At these frequencies, the polarized Galactic emission is from aspherical dust grains aligned in the Galactic magnetic field (see figure 1). This emission has a different dependence on frequency compared to the CMB signal, so with multi-frequency observations it is possible to clean much of it (see, e.g., Wolz et al. 2023). It has recently been pointed out (Nashimoto et al. 2020; Murokoshi et al. 2023) that the same aligned dust grains will preferentially absorb the CMB intensity along their long axes producing a polarization signal by absorption, in the same way that optical starlight is known to be polarized by Galactic dust (see Whittet 2022 for a textbook review). The impact of this absorption signal has not been quantified for B-mode polarization searches with ground-based CMB telescopes, which typically target regions of the sky with low foreground emission and are sensitive to degree-scale signals. The Simons Observatory (SO; Ade et al. 2019) is a new, world leading CMB observatory based in Chile. It will deploy six small-aperture telescopes (including two supplied by the UK) across six frequencies to search for primordial B-mode polarization. The purpose of this project is to simulate the new absorption foreground in the region of the sky to be observed by SO and to assess its impact on searches for primordial gravitational waves via B-mode polarization.

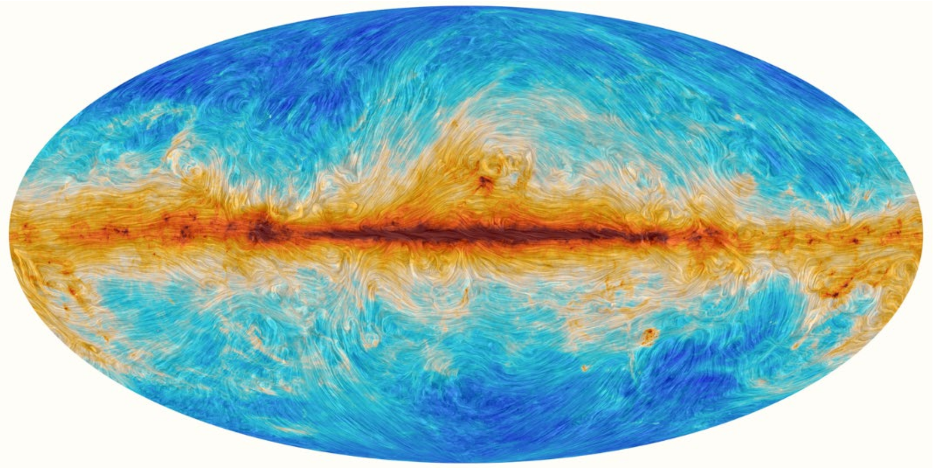

Figure 1,: Galactic magnetic field lines traced by dust polarization measurements by Planck at 353 GHz. Figure credit: Planck Collaboration.

Project Details

After getting to grips with the background CMB cosmology and a little of the theory of Galactic dust as a CMB foreground, the first step will be to produce estimates of the absorption signal over the footprint of the SO B-mode survey based on current templates for the dust emission there (which are derived from high-frequency data from Planck). The angular power spectrum of these maps will then be determined, quantifying the emission power as a function of angular scale, and used to assess the relative importance of the absorption signal. If it is found to be significant, mitigation techniques can be explored extending the multi-frequency cleaning techniques that have developed for SO and other experiments. An alternative direction to explore, if time permits, would be to refine the simulations of the absorption signal to account for variations in the dust properties along the line of sight.

Skills Required

- The project will use several software packages in Python, some of which will require modification.
- Strong mathematical skills are also required.
- Attendance at the Part-III courses Cosmology and Field Theory in Cosmology will be very helpful.

Useful References (List of important papers/review articles relevant to the project)

- Nashimoto, M., Hattori, M., Chinone, Y. CMB shadows: the effect of interstellar extinction on cosmic microwave background temperature and polarization anisotropy. ApJL 895, L21, 2020 (arXiv: 2005.06614)
- Murokoshi, T., Chinone, Y., Nashimoto, M., Ichiki, K., Hattori, M. Mitigating cosmic microwave background shadow degradation of tensor-to-scalar ratio measurements through map-based studies. ApJL 949, L29, 2023 (arXiv:2305.08931)
- Ade, P. et al. The Simons Observatory: science goals and forecasts. JCAP 02, 056, 2019
- Wolz, K. et al. The Simons Observatory: pipeline comparison and validation for large-scale B-modes. arXiv:2302.04276, 2023
- Kamionkowski, M., Kovetz, E. The quest for B modes from inflationary gravitational waves. Ann. Rev. Astron. Astrophys. 54, 227, 2016 (arXiv:1510.06042)

General References (List of papers referred to in the project)

- Whittet, D. Dust in the Galactic Environment. 3rd ed. IOP Publishing, 2022 (available as an ebook at https://iopscience.iop.org/book/mono/978-0-7503-3275-0.pdf)

Project 7: The spectroscopic signatures of magnetised disc winds

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Project Summary

This project involves the modelling of magnetised winds from protoplanetary discs with a view to determining what is the `spectroscopic fingerprint' of such winds. The basis for this modelling is a precomputed self-similar wind solution which provides the density and velocity field at all points in the wind: the task is then to compute the corresponding emission line flux and Doppler shift at every location and to use this to predict the spectroscopic signatures of the wind. These signatures include studying the shape of the emission line profiles in spatially unresolved data as well as exploring the `spectroastrometric signal' of such winds in partially resolved data. The aim of the project is to see if the spectroscopic signatures of magnetised winds are distinguishable from those generated by purely thermally driven winds.

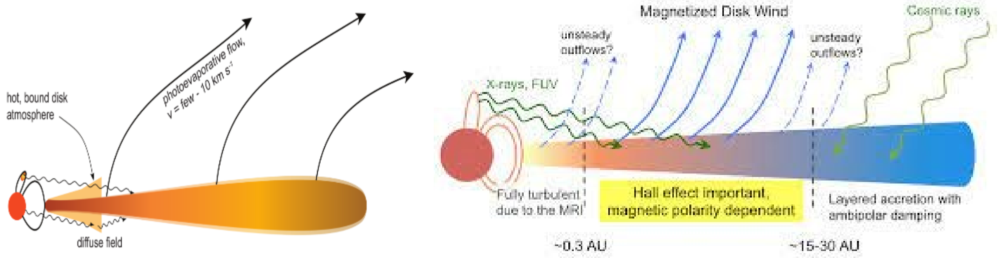

Figure 1.: A schematic of wind flow from protoplanetary discs. Left panel: the case of thermally driven winds heated by energetic radiation from the central star. Right panel: the case of a magnetically driven wind

Background

It is widely believed that protoplanetary discs lose mass in the form of winds from the disc surface. These winds may be thermally driven (i.e., be accelerated by pressure gradients associated with heating of the surface layers by X-ray or ultraviolet radiation) or else magnetically driven (i.e., accelerated by a combination of magnetic and thermal pressure gradients). While both these types of winds remove mass from the disc (and are thus important for clearing away potentially planet forming material: see e.g., Ercolano & Pascucci 2021), magnetically driven winds additionally exert a torque on the disc and thus drive accretion of material on to the star. Models of both types of winds are well developed (Clarke & Alexander 2016, Lesur 2021) and there have been several studies that examine the spectroscopic signatures of thermally driven disc winds, in particular focusing on the low velocity components of lines such as ionised neon and argon (Ballabio et al 2020). The purpose of this project is to undertake a similar study of the predicted properties of magnetically driven winds. These properties will be compared both with available observations and with the predictions of thermally driven models.

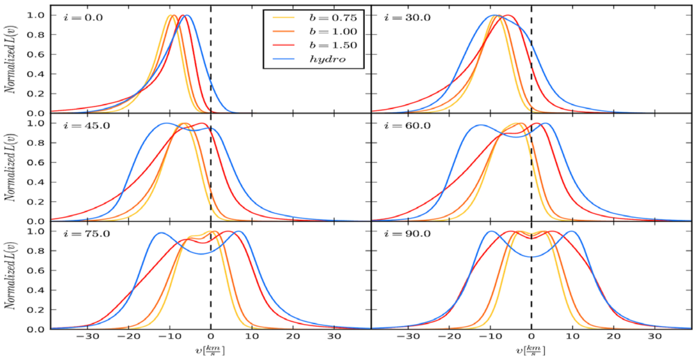

Figure 2.: An example of the line profiles of ionised neon at 12.8 microns produced by models for thermally driven winds by Ballabio et al 2021. The variety of line shapes correspond to different inclinations and density profile along the wind base.

Project Details

The starting point of the project is the pre-tabulated solution of Lesur (2021) which describes the density, temperature, and velocity field of a class of self-similar magnetically driven winds. The first task will be to use this model to populate a 3D grid and to compute the emission line flux and Doppler shift of emission from each cell as seen by an observer with a specified line of sight. The resulting emission line profile is then obtained through combining this emission from all locations in the wind. Variation of the line centroid velocity and full width at half maximum as a function of inclination can then be compared with observational datasets and with model predictions for thermally driven winds (Ballabio et al 2020). Depending on the rate of progress it may also be possible to extend this study so as to calculate the location of the centre of light of emission as a function of Doppler shift; such spectroastrometric datasets (Whelan et al 2021) are becoming available for the first time thanks to the higher spatial resolution that is attained through spectrometers on the world's largest telescopes such as the VLT. Again, model predictions could be compared with observations and with the predicted spectroastrometric signatures of thermally driven winds.

Skills Required

- The project will require programming in a language of the student's choice.
- A background in fluid dynamics, for example, the Part II course "Astrophysical Fluid Dynamics" is desirable.

Useful References (List of important papers/review articles relevant to the project)

- A systematic description of wind driven protoplanetary discs. Lesur, G. , 2021. A & A 650,35, Forbidden line diagnostics of photoevaporative disc winds. Ballabio, G. et al , 2020. MNRAS 496,2932
- Evidence for an MHD disc wind via optical forbidden line spectro-astrometry, Whelan, E. et al 2021, ApJ 913,43

General References (List of papers referred to in the project)

- The dispersal of planet forming discs: theory confronts observations, Ercolano, B. and Pascucci, I, 2021, Royal Soc. Open Science Vol 4, Issue 4, id 170114
- A self-similar solution for thermal disc winds, Clarke, C., Alexander, R., 2016 MNRAS 460,3044

Project 8: Symbiotic stars as progenitors of wide binary systems

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Project Summary

This project will investigate whether it is possible for symbiotic stars to form detached, wide binary systems consisting of a remnant of the donor and the compact accretor. The project will focus on modelling the time-evolution of such donor stars and comparing the results to observations of such systems.

Background

Symbiotic stars are interacting binary systems consisting of a red giant or a supergiant star that transfers matter to a white dwarf (WD) or a neutron star (NS). The optical spectrum of these systems consists of absorption features owing to the photosphere of the cool companion as well as a number of high-ionization lines and bright Balmer lines due to the presence of a luminous and hot compact accretor. There has been growing interest in understanding symbiotic stars and, owing to data from surveys such as WISE, 2MASS and Gaia we now have close to 350 such systems observed in our Galactic neighbourhood as well as in nearby galaxies (Belczynski et. al 2000; Akras et. al 2019). The orbital evolution of some of these systems (with donor masses less than about $2M_{\odot}$) is driven by stable mass transfer along with angular momentum loss owing to some sort of magnetic braking in the donor star. Once the donor star begins losing its convective envelope, its size increases and as a consequence, the system evolves to larger orbital separations. The mass-transfer stops once the envelope has been lost, when the donor shrinks back into its Roche lobe, giving rise to a wide binary consisting of the compact accretor and the low-mass helium-rich donor (Nelson et. al 2004). The goal of this project will be to model the evolution of such systems with our magnetic braking prescription, known as the Double Dynamo (DD) model of magnetic braking (Sarkar & Tout 2022; Sarkar et. al 2023). This has been used to explain the orbital evolution of main-sequence plus WD binaries, helium stars plus WD binaries and subgiant plus WD binaries. Because subgiant stars evolve to form red giants, the idea is that our DD model can, with due modification, be extended to explain the orbital evolution of red giants plus WD/NS binaries. This will further our understanding of how these systems form and evolve, as well as make the DD model a more robust magnetic braking mechanism in binary systems.

Project Details

You will make models of red giant stars with the Cambridge Stellar Evolution code STARS in an orbit with a point mass (WD/NS) accretor. You will modify the physics of our current DD model of magnetic braking to model red giant stars. You will then track the orbital evolution of the red giant plus the accretor when it is driven by angular momentum loss owing to the DD model of magnetic braking and stable mass transfer from the donor. You will verify whether our model trajectories agree with observations of orbital and donor properties from the catalogues of Belczynski et. al (2000), and its recent update by Akras et. al (2019) collected using 2MASS, WISE and Gaia surveys. If time permits, you can study the structure of the remnant of the donor star which may help us address the unsolved problem of how certain low-mass magnetic WDs form.

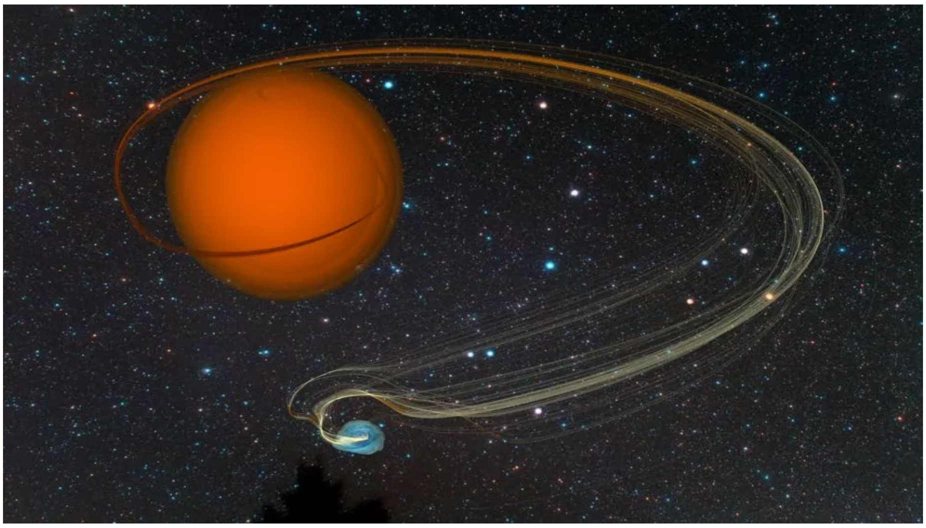

Figure 1: An artistic impression of the Draco C1 symbiotic binary star system showing material flowing off the red giant star onto its white dwarf companion. (Image credit: John Blondin/North Carolina State University)

Skills Required

- Part-II stellar evolution will be sufficient to follow the physics of this project.
- The student will use the STARS code, written in FORTRAN, to model the donor star. No prior knowledge of FORTRAN is required, but a basic understanding of coding is important. Knowledge of programming in Python is useful to analyse the output of the STARS code.

Useful References (List of important papers/review articles relevant to the project)

- Belczynski et. al 2000, “A catalogue of symbiotic stars” https://doi.org/10.1051/aas:2000280

General References (List of papers referred to in the project)

- Akras et. al 2019, “A Census of Symbiotic Stars in the 2MASS, WISE, and Gaia Surveys”https://doi.org/10.3847/1538-4365/aaf88c

- Belczynski et. al 2000, “A catalogue of symbiotic stars” https://doi.org/10.1051/aas:2000280
- Nelson et. al 2004, “Evolutionary Properties of Helium-rich, Degenerate Dwarfs in Binaries Containing Compact Companions” doi: 10.1086/421698
- Sarkar et. al 2023 “Evolved cataclysmic variables as progenitors of AM CVn stars” https://doi.org/10.1093/mnras/stad354
- Sarkar & Tout 2022 “A unified model for the evolution of cataclysmic variables” https://doi.org/10.1093/mnras/stac1187

Project 9: Streams in Nearby Galaxies

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Project Summary

Streams composed of stars and globular clusters are a consequence of hierarchical galaxy formation. Larger galaxies devour smaller ones. The smaller galaxy is destroyed by tidal forces, producing stellar streams. Many examples are known in the Milky Way, most famously the Sagittarius Stream. In nearby galaxies, streams are sometimes visible in photometry, but not always as they may be too faint to be detected. Nonetheless, individual globular clusters belonging to the stream can still be detected. Given the positions on the sky, the line-of-sight velocities and the proper motions (but not usually the distances) for the globular clusters in the nearby Andromeda Galaxy, can we identify ones that may lie in the same stream? This will provide us with a better understanding on Andromeda's formation history.

Background

The 'Field of Streams' is an iconic image with its own Wikipedia entry (https://en.wikipedia.org/wiki/Field_of_Streams). It shows multiple star streams in the Milky Way. It is dominated by the Sagittarius Stream.

For Milky Way stars, we are often privileged to possess six-dimensional phase space information (3 positions and 3 velocities). It is therefore easy to identify kinematic associations like streams. For nearby galaxies, the quality of the data is poorer — first, accurate distances to resolved stars or globular clusters are often unavailable and second the stream may be too faint to identify in photometry. This means it has to be identified by its signature in on-sky position and kinematics.

Project Details

We begin by assuming a stream is an orbit. Several objects are observed in projection and are presumed to be members of a tail of a tidal stream. We are interested in using this information to identify the stream and to make inferences about the potential of the host galaxy. For each object, the line-of-sight velocity vz and two of the three positional coordinates, x and y, are known to good accuracy. There may also be proper motions and line of sight distances available, but with much larger error bars. We assume that the galactic potential is spherical. This has the consequence that the motion takes place in a single plane. We then wish to evaluate the probability that an object possesses particular values of energy and angular momentum given its projected coordinates (x; y; vz), orbital plane P and an assumed spherical halo potential with total mass M. We then wish to apply the algorithm both to identify streams in the set of ~150 globular clusters belonging to the nearby Andromeda galaxy and to use the identified streams to measure the total mass M of the dark halo of Andromeda.

A disruption of a largish dwarf galaxy on a nearly radial orbit may also lead to a production of a system of shells rather than. a stream (Merrifield & Kuijken 1998, Dong Paez et al 2022). The Project will also consider the problem of identifying and modelling a dynamically young system of shells from projected data (x,y; vz). This has been considered recently by Dey et al. (2023) in the context of M31.

There are further elaborations possible if the project goes swiftly. This includes loosening the assumptions that a stream is an orbit and that the potential is spherical, as well as including chemical information on the clusters, examining the use of machine learning and looking at prospects for the future with data on nearby galaxies (eg Centaurus A) from the Vera Rubin Telescope.

Skills Required

- Part II Galaxies course (or an equivalent) is essential, as is a standard undergraduate course on Classical Mechanics.
- Programming skills (either in Mathematica, Python, C or Matlab) are desirable.

Useful References (List of important papers/review articles relevant to the project)

- Binney J., Tremaine S., 2008, Galactic Dynamics, Princeton University Press
- Landau, L, Lifshitz, E.M. 1976, Classical Mechanics

General References (List of papers referred to in the project)

- Belokurov V., Zucker D.B., Evans N.W., Gilmore G., et al., 2006, ApJL, 642, L137
- Dey A., Najita J.R., Koposov S.E., Josephy-Zack J., Maxemin G., Bell E.F., Poppett C., et al., 2023, ApJ, 944, 1.
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- Mackey D., Lewis G.F., Brewer B.J., Ferguson A.M.N., Veljanoski J., Huxor A.P., Collins M.L.M., et al., 2019, Nature, 574, 69.
- Malhan K., Ibata R.A., 2019, MNRAS, 486, 2995
- Merrifield M.R., Kuijken K., 1998, MNRAS, 297, 1292.
- Pearson S., Clark S.E., Demirjian A.J., Johnston K.V., Ness M.K., Starkenburg T.K., Williams B.F., et al., 2022, ApJ, 926, 166.

Project 10: Unveiling the Hidden Dance of Galaxies: Exploring Galaxy Formation Physics Through Cosmic Surveys

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Project Summary

Cosmological surveys have become increasingly sensitive to galaxy physics at scales of 1 Mpc, with the claim that galaxy formation physics suppresses the amount of cosmological structure at the scale of galaxy clusters and below. This has now been suggested from weak lensing data (Arico et al., 2023) as well as pressure profiles in clusters (see Fig.1; Panday et al., 2023). Such an effect should therefore also be present in the peculiar velocity field surrounding galaxies that is mapped by cosmological redshift surveys. Using FABLE cosmological simulations (Henden et al., 2018) of galaxy formation this project will explore the effect of galaxy physics on the velocity structure, in order to assess whether these different measurements are complementary in our ability to learn galaxy formation physics from cosmological surveys.

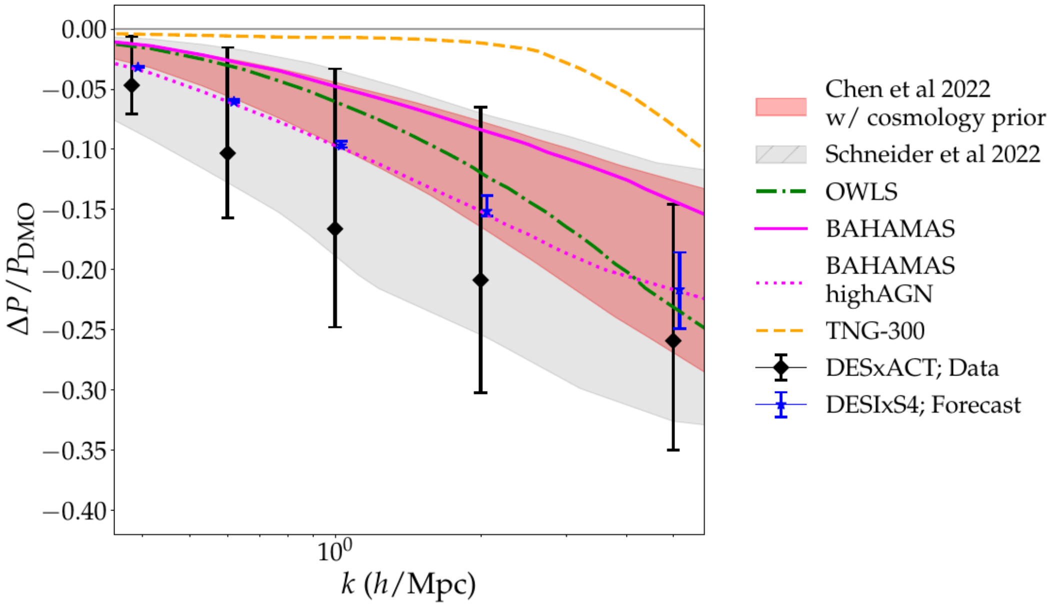

Figure 1.: The amount of power spectrum suppression relative to dark matter only model as inferred from DES and ACT data using pressure profiles of clusters (from Panday et al. 2023). The amount of suppression in the power spectrum is linked to the effects on baryon feedback and galaxy formation. The analyses presented used a cross-correlation between optically selected clusters from DES survey and thermal SZ effect as measured by ACT CMB experiment. The data are compared to a number of simulations, with varying models of galaxy formation and galactic feedback.

Background

The evolution of cosmological structure in the Universe is primarily governed by dark matter, in the standard Lambda-CDM model (see Dodelson & Schmidt, 2020, for a review on cosmology). This structure spans a cosmic web of knots and filaments that host the formation of galaxies (Zel'dovich 1970) – a picture that is confirmed by a number of numerical simulations. The amount of structure in cosmological surveys is often expressed in terms of e.g., variance of the density field in spheres of a given scale – generally termed a power spectrum. Most simulations agree that this variance, or power spectrum, should slowly decrease as the scale of the sphere decreases. This behaviour is suppressed due to non-linear evolution of gravitational collapse and is enhanced when the pressure forces of baryons dominated over the gravitational potential (Chisari et al., 2019). These effects have been heavily studied in terms of the matter density distribution in galaxy formation simulations and compared to increasingly larger sample of data (Schaye et al. 2023). Several independent groups have shown that such a signal appears to be present in the weak gravitational lensing data of DES and KiDS (e.g., Arico et al., 2023), where correlations between galaxy shapes are sensitive to the cumulative amount of variance, or power spectrum, between those galaxies and us. Similar signal has been also seen in the thermal Sunyaev-Zel'dovich (Sunyaev & Zel'dovich, 1970) measurements of the pressure profiles in massive clusters. If the effects of galaxy formation are indeed present in the matter density distribution, then due to mass conservation law similar effects should also be present in the velocity field of matter. Cosmological redshift surveys measure redshifts of distant objects as an indicator of their distance from us (Chen et al. 2021). However, aside from the Hubble flow that depends on the distance, redshift also contains information of the local velocity field of these objects, and therefore the velocity field of matter. Not only might the velocity field respond differently to galaxy formation than the density field, but the redshift surveys provide a completely independent view of the question of galaxy formation effects on cosmological power spectrum.

Project Details

The project will involve:

- Analysing cosmological simulations of galaxy formation FABLE in order to measure power spectra of matter and velocity distributions,
- Compare the effects of different galaxy formation models on both matter and velocity power spectra (code Pylians; Villaescusa-Navarro, 2018)
- Assess what environments (Halo masses, Blackhole masses, etc.) contribute most to matter and velocity power spectra,
- Infer correlations between different physical observables (e.g., velocity power spectrum suppression, gas fractions in clusters and thermal Sunyaev-Zel'dovich (tSZ) effect),
- Predict the effect of galaxy formation on cosmological redshift survey measurements (such as Chen et al., 2021)

Skills Required

- The project will require programming in Python. Knowledge of C would be beneficial.
- (Some of) the content of the Part II courses "Physics of Astrophysics", "Relativity" and "Introduction to Cosmology" and the Part III course "Formation of Galaxies" should all be relevant.

Useful References (List of important papers/review articles relevant to the project)

- Dodelson & Schmidt (~~2003,~~2020), *"Modern Cosmology",* Amsterdam: Academic Press

- Panday, S et al. (2023), https://arxiv.org/abs/2301.02186
- Arico, G. et al. (2023), https://arxiv.org/abs/2303.05537
- Chen, S.-F et al. (2021), JCAP, 2022, 02, 008
- Henden, N.A. et al. (2018), MNRAS 479, 4
- Villaescusa-Navarro, F. (2018), Pylians, https://pylians3.readthedocs.io/en/master/

General References (List of papers referred to in the project)

- Zel'dovich, Y. B. et al. (1970), A&A, 5, 84
- Sunyaev, R.A. & Zel'dovich, Y.B. (1970), Astrophysics and Space Science, 7, 1, 3
- Schaye, J. et al. (2023), https://arxiv.org/abs/2306.04024
- Chisari et al. (2019), The Open Journal of Astrophysics, 2, 4

Project 11: Tracing the chemical and dynamical structure of the Milky Way disk with open clusters

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UTO: N. W. Evans (nwe@ast.cam.ac.uk)

Project Summary

Open clusters have been providing a useful arena for studying the stellar formation and evolution. An open cluster typically consists of a single stellar population, with its stars born at the similar time and location. It is also sparse in density, making it easier to study the individual member stars. As there are several thousand open clusters known in our Galaxy so far, open clusters can help us to trace the chemistry and the stellar age distribution of the Galactic disk in detail. In addition, open clusters' orbit can be traced to seek their original birthplace.

Based on this multi-dimensional information, we can study potential associations between the clusters and study the chrono-chemo-dynamical structure of the Galactic disk. The result can be further compared with predictions from different disk formation models, as different formation mechanism can leave different trend in age-metallicity-kinematics which can be checked from above analysis.

Background

A typical open cluster consists of a single stellar population as its stars are formed at the similar time and location, from the same materials. Because of its relative sparseness in spatial distribution, its member stars can be resolved more easily and studied individually. This leads to a better constraint on its properties such as age, chemical abundances, and distance than for the case of some isolated stars.

With such advantages, open clusters have been useful tracers for studying the chemical and dynamical structure of the Galactic disk. For example, the Galaxy's chemical abundance gradients (e.g., negative [Fe/H] gradient along Galactic radius) and the effects of radial migration in the disk are important for understanding the chemical evolution history of our Galaxy (see e.g., Doner et al. 2018, Netopil et al. 2021, Myers et al. 2022), but until recently there have been limitations on such study mostly due to the limit on the sample size and inhomogeneity in data.

The recent progress in large-scale spectroscopic and astrometric surveys, such as APOGEE (Blanton et al. 2017), GALAH (Martell et al. 2017), and Gaia (Gaia Collaboration et al. 2016), has revolutionised the field with large and comprehensive new datasets. In addition, the Open Cluster Chemical Abundances and Mapping (OCCAM; Myers et al. 2022) survey provides a list of stars in 150 open clusters, with 16 chemical elemental abundances based on APOGEE DR17. Cantat-Gaudin et al. 2020 also provides useful parameters for open clusters including the cluster radius and age estimates. With various tools for Galactic Dynamics such as AGAMA (Vasiliev 2018), and suitable multi-dimensional clustering algorithms, the chemistry and orbital dynamics of individual stars and clusters will be studied in great detail which will expand our understanding on the chemo-dynamical evolution of the Galactic disk.

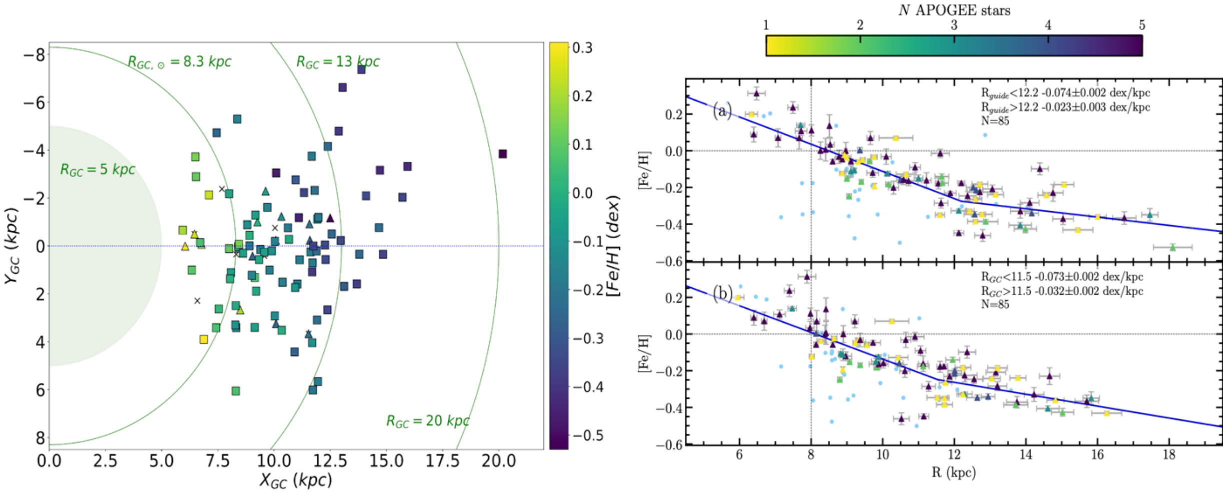

Figure 1.: From Myers et al. (2022). Left: The Galactic X–Y distribution of a sub-sample of open clusters in OCCAM catalogue, colour-coded with their mean metallicity. The "high quality" clusters are marked with squares, lower quality clusters with triangles and crosses. Right: Metallicity gradients mapped as a function of guiding radius (upper panel), and current radius (bottom panel), along with a bilinear fit. Clusters flagged as potentially unreliable are shown as light blue circles. Colour-coding indicates the number of OCCAM member stars per cluster.

Project Details

We will use a combination of spectroscopic and astrometric data from APOGEE, GALAH, and Gaia. A combination of APOGEE's OCCAM and Gaia provides a list of stars in ~100 "high quality" open clusters with chemical and astrometric information which will serve as a useful starting point for the project. The age of open clusters (Cantat-Gaudin et al. 2020) will also be considered in our analysis. The Gaia XP dataset will provide further metallicity estimates for many of the open cluster members as well. The project will start from acquiring necessary information from the available survey datasets, and from deriving useful parameters (e.g., stellar orbits) from the observables (e.g., astrometric information).

With this rich dataset in hand, we will perform multi-dimensional analysis based on clustering algorithms to study the chrono-chemo-dynamical trends among the open clusters which will help us to understand the chemical and dynamical structure of the Galactic disk, such as chemical abundance gradients and radial migration. This will provide an opportunity to compare the observed trends from the data with the predictions from different disk formation models.

Skills Required

- Good Python skills are desired.
- Stellar Dynamics and Structure of Galaxies (Part II) and The Life and Death of Galaxies (Part III) are desired.

Useful References (List of important papers/review articles relevant to the project)

- The Open Cluster Chemical Abundances and Mapping Survey: VI. Galactic Chemical Gradient Analysis from APOGEE DR 17. Myers et al. (2022), arXiv:2206.13650
- The Galactic metallicity gradient shown by open clusters in the light of radial migration. Netopil et al. (2021), MNRAS, 509, 421N

- Painting a portrait of the Galactic disc with its stellar clusters. Cantat-Gaudin et al. (2020), A&A, 640A, 1C
- The Open Cluster Chemical Abundances and Mapping Survey: VII. APOGEE DR17 [C/N]-Age Calibration. Spoo et al. (2022), AJ, 163, 229S
- Discovery of new retrograde substructures: the shards of ωCentauri? Myeong et al. (2018), MNRAS, 478, 5449M
- AGAMA: action-based galaxy modelling architecture. Vasiliev (2019), MNRAS, 482, 1525V

General References (List of papers referred to in the project)

- Cantat-Gaudin et al. (2020), A&A, 640A, 1C
- Netopil et al. (2021), MNRAS, 509, 421N
- Donor et al. (2018), AJ, 156, 142
- OCCAM: Myers et al. (2022), arXiv:2206.13650
- APOGEE: Blanton et al. (2017), AJ, 154, 28
- GALAH: Martell et al. (2017), MNRAS, 465, 3203
- Gaia: Gaia Collaboration et al. (2016), A&A, 595, A1
- Vasiliev (2019), MNRAS, 482, 1525V

Project 12: Timing the Last Major Starburst of the Milky Way

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UTO: Vasily Belokurov (vasily@ast.cam.ac.uk)

Project Summary

Approximately 8-10 billion years ago, the Milky Way (MW) experienced its last major merger with a dwarf galaxy (Gaia-Sausage/Enceladus, GSE). As a result of this merger, a large number of GSE stars were deposited into the MW halo on highly radial orbits - orbits that can be recovered today. But GSE did not just deposit stars into the MW, it also brought with it a fresh reservoir of gas from which new stars formed - marking the final burst of global star formation in the MW. The precise timing of the burst, when in the MW's history and for how long it occurred, along with the chemical signatures of the star-forming gas (a direct link to the long-lost GSE), are encoded in the stars formed from this event. Using samples of stars from spectroscopic surveys (APOGEE, GALAH) and Gaia data, this project aims to localise the population of stars that formed from this burst and perform Galactic Chemical Evolution (GCE) modelling to answer the question of when and how these stars formed. This project has the potential to provide a timestamp on the last major merger of the MW, marking the turnover from chaotic to quiescent star formation in our galaxy.

Background

Recent data releases from the Gaia mission (DR2, DR3) have triggered a revolution in our understanding of the assembly history of the Milky Way (MW). Leveraging this unprecedented dataset of nearby stars, a plethora of past merger events between the MW and dwarf galaxies (dGal) have been discovered. The most prominent example being the Gaia-Sausage/Enceladus (GSE) dwarf (Belokurov et al. 2018, Helmi et al. 2018) depicted in the left panel of Fig.1. A critical next step in understanding the MW assembly history is to characterise the last major merger that took place, between the GSE and the MW. Thus far, efforts have been focused on uncovering the characteristics of the GSE prior to infall, while little work has been done towards understanding the impact of the GSE merger on the primordial MW.

Recovering stars in the MW halo associated with different star formation environments is a difficult task. Thankfully, stars born as a result of the same star-forming event have been shown to share common chemo-dynamical properties and ages - providing a link to their formation environment. Within the MW a number of distinct stellar populations have been identified based on their specific trends in chemistry and orbital dynamics (see e.g., Belokurov et al. 2022, Myeong et al. 2022).

Exploiting the similarities of coeval stellar populations in chemodynamics, Myeong et al. 2022 applied a Gaussian Mixture Model to “unmix” the MW halo. They recovered several known substructures, including the GSE, in addition to a new structure - Eos. Given the appearance of Eos at a given metallicity ([Fe/H]) - a proxy for lookback time, and the rapid increase in [Mg/Fe] - a marker of star formation, Myeong et al. identified Eos as being a starburst associated with the GSE merger. One scenario to explain Eos is that while GSE merged with the MW, gas from the dGal was stripped from the main body by the tidal field of the larger MW. As the gas flowed into the MW, tidal interactions between the two galaxies triggered star formation in one or both objects. An example of tidal interactions between dwarfs triggering star formation is shown in the right panel of Fig. 1 where the interacting galaxies NGC 4485 and NGC 4490 both show clumpy regions of bursty star formation.

Although we now believe we have localised stars born during the interaction between the MW and Eos, the specifics of how, when and where these stars formed is still unknown. It is not clear whether the stars formed within the primordial MW, from GSE gas, a mix of GSE and primordial MW gas, or within the GSE itself. Regardless of where these stars formed, they represent the last major starburst event within the primordial MW system - demanding a closer look.

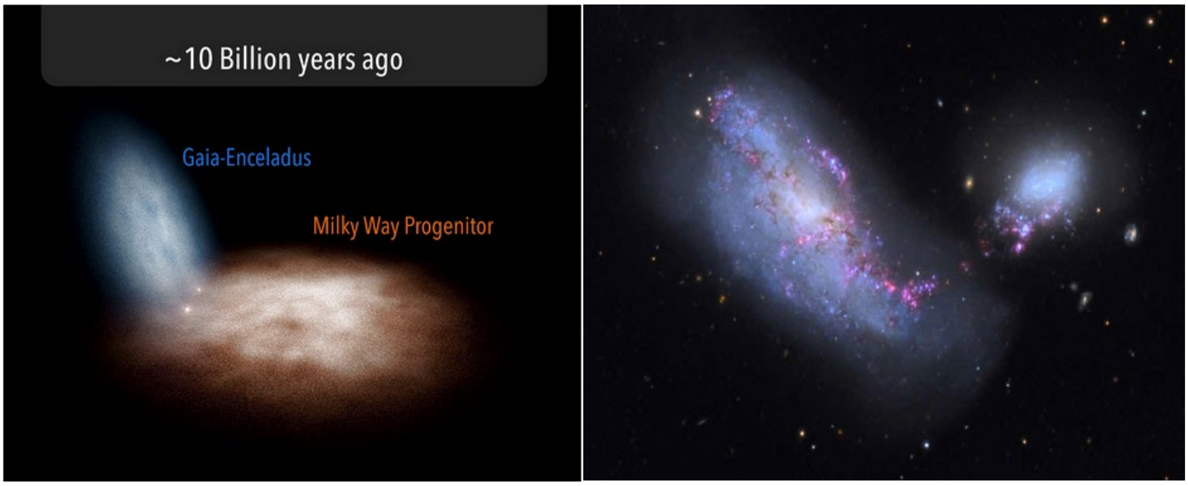

Figure 1.: Left: Artist depiction of the last major merger of the MW, between the Gaia-Enceladus-Sausage dwarf galaxy and the primordial MW. While much work has gone towards understanding GSE, little has gone into understanding the impact of the merger on the star formation history within the MW. (Gabriel Pérez Díaz, SMM, Instituto de Astrofísica de Canarias.) Right: the merging galaxies NGC 4485 and NGC 4490 undergoing starbursts (seen as star-forming clumps) triggered by their ongoing interactions (HST).

Project Details

To understand and characterise the last major starburst of the MW, we need to i) isolate a sample of stars within the MW that were born in this burst and ii) fit the chemical evolution of these stars in multiple spaces to extract the star formation history of the burst. The first point is best-addressed in chemo-dynamical space, combining information about the chemical abundances of the stars (the ratio of elements within the atmospheres of evolved stars) with knowledge of the stellar orbits.

Identifying structure in chemo-dynamical space has already been shown to be successful in detecting major contributions to the MW halo (see Fig. 2 from Myeong et al. 2022), namely the GSE and Eos. Galactic chemical evolution predictions inform us that a rapid increase in light elements like Al or Mg (a member of the “α-elements”), over a small change in metallicity ([Fe/H]) is the result of rapid and efficient star formation. This signature is seen clearly, for example, in the Eos (blue) and Aurora (red) components shown in Fig 2, in panels *a* and *e*. To select bonafede Eos stars for the study, the student will first use improved Gaussian Mixture Models of the MW in chemo-dynamical space and explore alternative selection criteria.

To model the characteristics of the burst including; when the burst began, its duration, star formation rate and the composition of the star-forming gas, we will use galactic chemical evolution modelling tools such as flexCE or VICE. These tools can predict the chemical abundances of stars (up to ~20 elements) formed over time as a result of star formation within a galaxy. To do this, GCE codes make some assumptions of the physical processes governing the movement of gas into and out of the system as well as the star formation efficiency, nucleosynthetic sources, sites of element formation and the duration and strength of star formation bursts. The student will start by using the canonical star bursting models within flexCE or VICE to model Eos under simple assumptions, comparing the predicted abundances associated with different star formation bursts to the observed chemical signatures of Eos.

Although details vary between simulations ((e.g., Grand et al. 2020, Renaud et al. 2021), it appears likely that Eos formed from a mixture of gas from both GSE and the primordial MW. As such, we would also like the student to explore different gas mixtures to simulate contributions from both the primordial MW and GSE, with some code development of either flexCE or VICE. The student could also look into simulating simultaneous star formation within two galaxies (the primordial MW and GSE) through evolving each and adjusting the composition of the mixed gas. If time allows, the same machinery developed for the project could be applied to study the MW's star formation history at an earlier stage of its life, based on the known properties of the ancient MW in situ population, Aurora (Belokurov et al. 2022, Myeong et al. 2022).

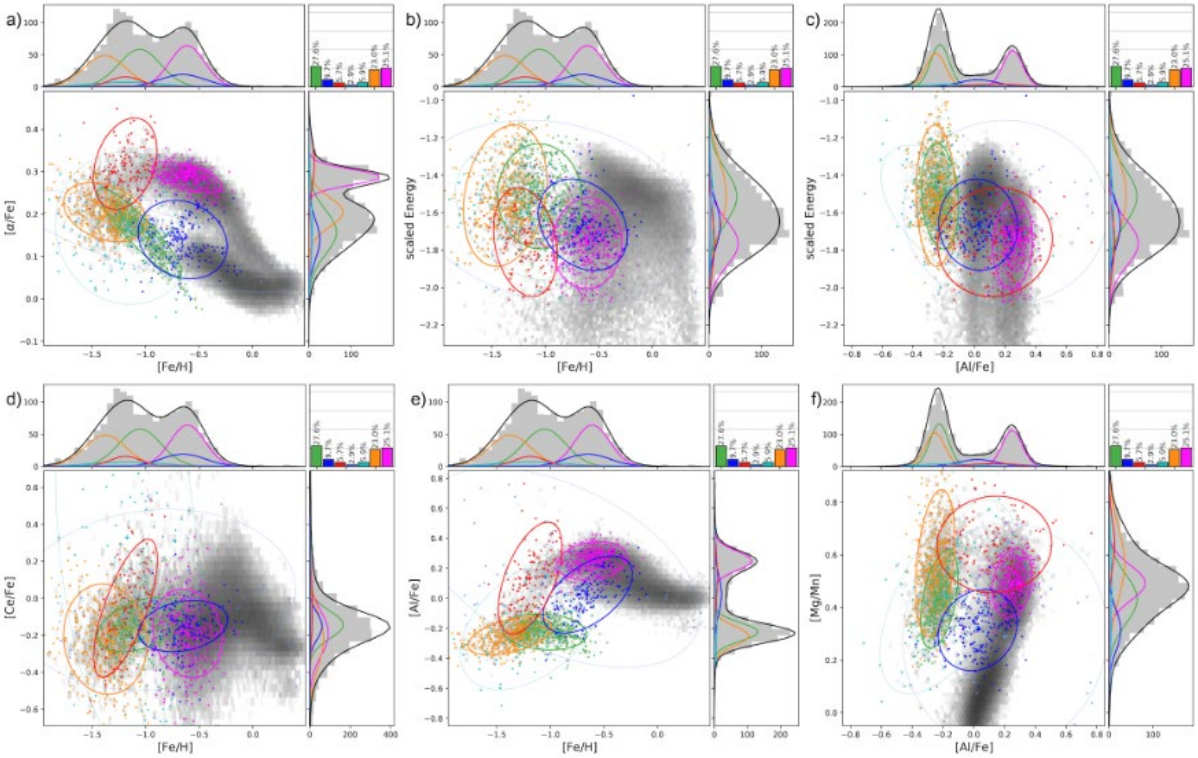

Figure 2.: Distribution of five MW halo components identified in chemo-dynamical space across different chemical abundance ratios from Myeong et al. 2022. Two components of note are the blue component - Eos and the green and orange components - Gaia-Sausage/Enceladus. Note the rapid increase in metallicity and [α/Fe] (panel a) and [Al/Fe] (panel e), reflecting rapid and efficient star formation.

Skills Required

- Strong python programming skills are a must. Prior knowledge of chemical abundances and large spectroscopic surveys would also be helpful, but not necessary.
- Relevant Part II/Part III courses include, Stellar Dynamics and Structure of Galaxies, Introduction to Astrophysics, Structure and Evolution of Stars, The Life and Death of Galaxies.

Useful References (List of important papers/review articles relevant to the project)

- From dawn till disc: Milky Way's turbulent youth revealed by the APOGEE+Gaia data. Belokurov et al. (2022), MNRAS, 514, 689B
- Milky Way's Eccentric Constituents with Gaia, APOGEE, and GALAH. Myeong et al. (2022), ApJ, 938, 21M

General References (List of papers referred to in the project)

- Information on the flexCE code: Inflow, Outflow, Yields, and Stellar Population Mixing in Chemical Evolution Models. Andrews et al. (2016), ApJ, 835, 2
- Information on VICE Galactic Chemical Evolution code: https://vice-astro.readthedocs.io/en/latest/science_documentation/index.html#scidocs
- Examples of Galactic Chemical Evolution modelling: APOGEE Chemical Abundance Patterns of the Massive Milky Way Satellites. Hasselquist et al. (2021), ApJ, 923, 2

Project 13: Predicting the Capabilities of Adaptive Optics Instrumentation for the Study of Distant Star Clusters

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UTO: Vasily Belokurov (vasily@ast.cam.ac.uk)

Project Summary

In the era of large space-based telescopes, ground-based telescopes must operate at the very limit of their capabilities to stay competitive. In terms of spatial resolution, this requires adaptive optics to correct the destructive effects of the Earth's atmosphere and push performance to the diffraction-limited regime. The MCAO-Assisted Visible Imager and Spectrograph (MAVIS) will enable the Very Large Telescope to operate in this regime in the visible part of the spectrum for the first time. To predict the capabilities of MAVIS before it goes on-sky the MAVIS Image Simulator (MAVISIM) was created, combining information from adaptive optics simulations with scientifically motivated test cases. Thus far, MAVISIM has been used to show that MAVIS could detect the dynamical signature of an intermediate mass black hole inside a dense globular cluster. In the next iteration of MAVISIM, focused on photometry, we would like to show that MAVIS could resolve stellar populations in star clusters out to 100 kpc - at the limit of the capabilities of the Hubble Space Telescope. In this project, you will work on developing MAVISIM 1.2 to create polychromatic images and directly contribute to the development of next generation instrumentation. This is the ideal project for someone with a desire to understand the flowdown of science cases to engineering specifications.

Background

Independent of the telescope design, and mitigated only by the choice of site, the Earth's atmosphere is the limiting factor for ground-based telescopes. This is due to the constant motion of the atmosphere which is largely an effect of thermal differentials and bulk motions (jet streams). Observationally, the turbulence is qualified as “seeing", an unavoidable effect that makes it all but impossible to achieve the theoretical diffraction limit of the system. Adaptive optics (AO) is the only solution available to ground-based telescopes to correct for atmospheric distortion. As such, almost all 8m-class telescopes are equipped with AO instruments, while all 30m-class telescopes are being designed with AO systems as integral parts of the telescope design.

Thus far, most AO systems, both in operation and in the design phase, operate in the near-infrared (near-IR). One reason for this is that the rate of the AO-loop inversely scales with the wavelength of the light, making visible AO systems incredibly computationally intensive. MAVIS, the MCAO-Assisted Visible Imager and Spectrograph, will be the first wide-field AO system to operate in the visible (380-900 nm), allowing the 8m Very Large Telescope to continue to compete with, and eventually surpass the aging Hubble Space Telescope.

To simulate the capabilities of MAVIS before the instrument goes on-sky (in 2030), we have written the MAVIS Image Simulator (MAVISIM, Monty et al. 2021). Thus far, MAVISIM has shown that MAVIS could detect the signature of an intermediate mass black hole in the centre of a globular cluster (something that is predicted to exist but has yet to be discovered). This simulation served to demonstrate the predicted astrometric capabilities of MAVIS. But as of yet, MAVISIM has not been used to perform a study of the photometric capabilities of the instrument - the next step to verify that the instrument will achieve strict performance metrics.

One of the proposed photometric science cases for MAVIS is the exploration of star clusters beyond the Milky Way (MW). Given their high central densities, star clusters push AO systems to their limit to resolve as many individual stars as possible. Thus far, only limited studies have been performed to examine star clusters beyond the MW. The most distant star clusters hosted by a Local Group galaxy are the Fornax dwarf galaxy globular clusters (circled in the left panel of Fig. 1). These clusters are of particular interest given that their existence poses issues within our current cosmological paradigm (ΛCDM, the “Fornax Timing Problem”).

HST colour magnitude diagrams of the clusters (observational analogues of the Hertzsprung Russell Diagram, shown in the right panel of Fig. 1) show the magnitude depth achievable by HST (~V band 26), shallow compared to the predicted limiting magnitude of MAVIS (V band ~ 29 magnitude). To pin down cluster characteristics, like the initial mass function, cluster age and total mass, detecting low-mass stars at fainter magnitudes is essential. An example monochromatic image from MAVISIM of the star cluster Fornax 5 is shown in the right panel of Fig. 2. A comparison image from HST is shown in the left panel of Fig. 2 - highlighting the better spatial resolution of MAVIS in the inner parts of the cluster. The next step is to prove that MAVIS could measure these objects before it goes on-sky.

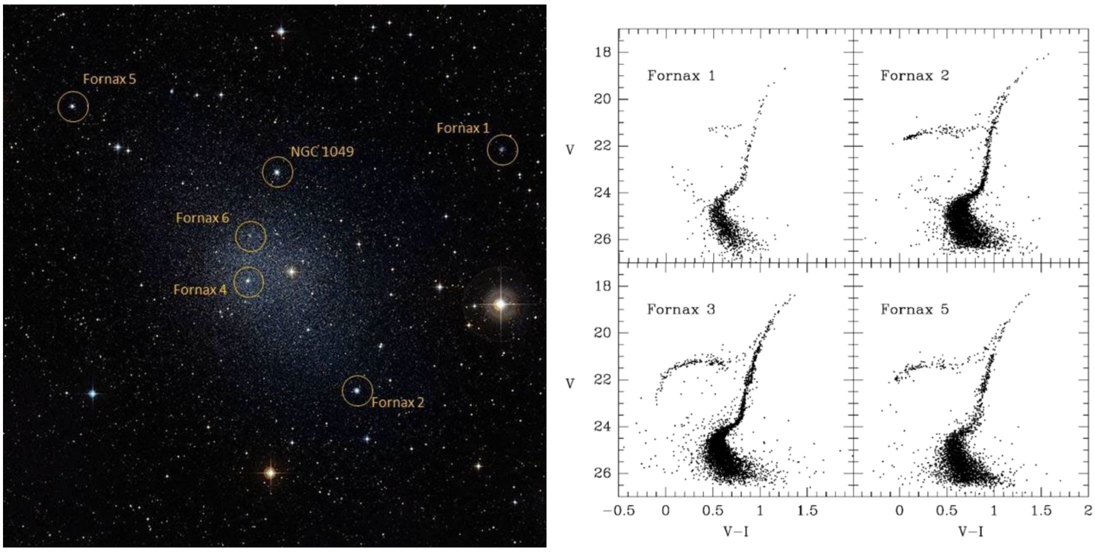

Figure 1.: : (Left) HST image of the Fornax dwarf galaxy, with the six confirmed globular clusters circled. (Right) Hubble Space Telescope colour magnitude diagrams of four of the Fornax clusters, note the limiting magnitude of 26 achieved by HST (vs. the predicted depth of MAVIS, V ~ 29) Buonnano et al. 1997.

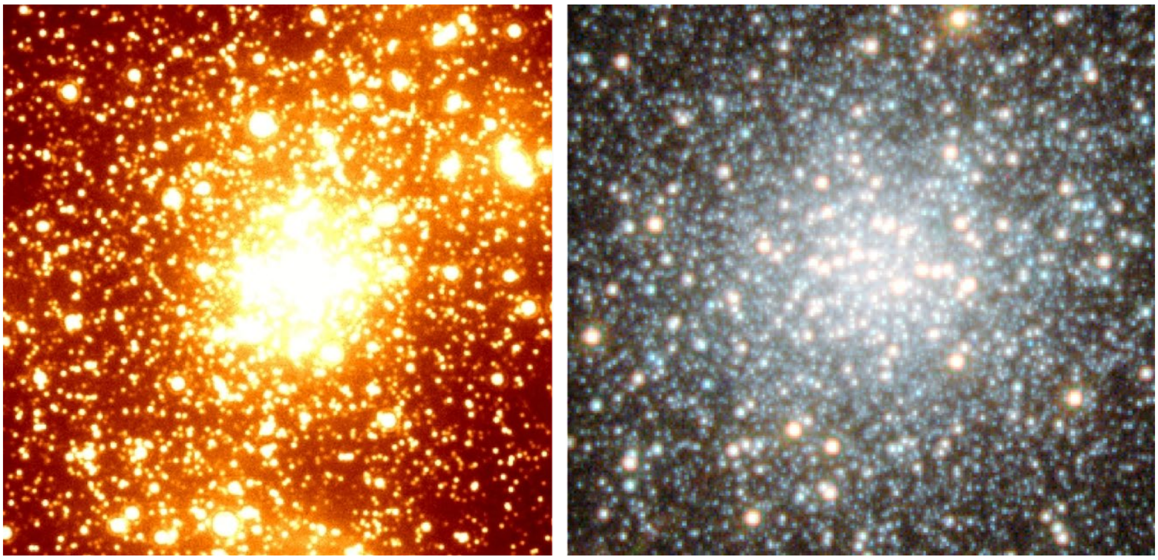

Figure 2.: (Left) monochromatic image generated by MAVISIM of the star cluster, Fornax 5. (Right) Hubble Space Telescope image of Fornax 5. Note the difference in spatial resolution between the two instruments. The 8m aperture of the VLT, coupled with the AO-correction provided by MAVIS will resolve individual stars down to fainter magnitudes in this enigmatic cluster.

Project Details

At the moment, MAVISIM only models monochromatic point sources (stars), as such the first step to building the polychromatic version of MAVISIM 1.2 will be to create realistic input catalogues of stellar photometry across a broad range of wavelengths. To do this, the student will explore different modelling tools to simulate the spectral energy distributions (SEDs) of different stellar types. One example tool they will explore is SPISEA (Hosek, 2020), a tool to simulate populations of stars found in star clusters.

The first step in this project will be to accurately model a population of stars across the MAVIS photometric filters, followed by a study into how best to capture this information within the MAVISIM simulation framework. To distribute the stars on-sky in a realistic way, the stellar populations will need to be coupled to a realistic globular cluster density profile (e.g., the King model). Creating a realistic model of a globular cluster complete with binary stars, multiple stellar populations and mass segregation is a natural extension of this project if the student shows a keen interest in this component.

Following the development of MAVISIM 1.2, the next step is to explore recovering colour magnitude diagrams from the simulated images. This will involve performing PSF-fitting photometry to extract the stellar positions and magnitudes in the simulated filters. To do this, the student will experiment with PSF-fitting photometric tools (e.g., DAOPhot, StarFinder2, PSFEx) to extract formation from the simulated images.

As part of this project, the student will be expected to work closely with key scientists within the MAVIS team and interact with the larger MAVIS consortium as a whole. The student will present their results as part of MAVIS deliverable documentation and report their results at regular progress meetings/design reviews. Having access to a large ESO-supported, international instrument consortium will provide the student with unique networking opportunities and access to world-class scientists and engineers. Finally, if the student is motivated, the results of this study could be published in a journal like MNRAS.

The paper structure could follow the format of Monty et al, 2021, showcasing the improvements to MAVISIM and demonstration of a new science case (resolving extragalactic globular cluster centres)

Recommended Part II and Part III courses include Structure and Evolution of Stars and Stellar Dynamics and Structure of Galaxies or The Life and Death of Galaxies.

Skills Required

- Strong python programming skills are a must.
- Prior knowledge of adaptive optics, star clusters and stellar evolution would be an asset.

Useful References (List of important papers/review articles relevant to the project)

- Towards realistic modelling of the astrometric capabilities of MCAO systems: detecting an intermediate-mass black hole with MAVIS. Monty et al. (2021), MNRAS, 507, 2.
- MAVIS on the VLT: A Powerful, Synergistic ELT Complement in the Visible. Rigaut et al. (2021). The Messenger, vol. 185, p. 7-11.
- MAVISIM documentation: https://mavisim.readthedocs.io/en/latest/

General References (List of papers referred to in the project)

- Phase A Science Case for MAVIS -- The Multi-conjugate Adaptive-optics Visible Imager-Spectrograph for the VLT Adaptive Optics Facility. McDermid et al. (2020), arxiv: https://ui.adsabs.harvard.edu/abs/2020arXiv200909242M/abstract
- Multiconjugate Adaptive Optics for Astronomy. Rigaut & Neichel. (2020), Annual Review of Astronomy and Astrophysics, vol. 56, p.277-314
- SPISEA: A Python-based Simple Stellar Population Synthesis Code for Star Clusters. Hosek et al. (2020), AJ, 160, Issue 3
- SPISEA code documentation: https://spisea.readthedocs.io/en/latest/

Project 14: The interplay between planetary migration and accretion in young protostellar discs

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Project Summary

Protostellar discs are the link between stars and planets: they form with the star, and they are the environments in which planet formation takes place. Many discs exhibit substructures that are consistent with - and often interpreted as - the theoretically expected signature of planet-disc interaction (Andrews et al. 2018). Under the hypothesis of the planetary interpretation, a robust conclusion is that a substantial part of the planet formation process must overlap with the time when protostellar discs are likely to be self-gravitating and, possibly, gravitationally unstable.

In this project we will study the interplay between migration and accretion in young protostellar discs. The aim is to understand whether planetary cores are able to grow enough to stop the migration, and eventually becoming gaseous giants, akin to those observed in ALMA data. We will tackle these questions with analytical estimates, hydrodynamical and radiative transfer simulations.

Background

The way in which planets form in protostellar discs is still under debate. Indeed, the two main theories fail in explaining the formation of planetesimals and planetary cores. The first theory, known as Core accretion (Goldreich & Ward 1973), faces challenges due to the significant timescale involved, and the metre sized barrier (Weidenschilling 1977). The second theory, Gravitational instability (Boss 1997), is more likely to explain the formation of stellar companion rather than planets.

A possible solution to the conundrum of how to form planetary cores has been firstly proposed by Rice et al. 2004, 2006, and then further explored by Booth & Clarke 2016, Baehr & Zhu 2021 and Longarini 2023a, 2023b. According to this model, solid cores can form in the outer disc from dust concentration and collapse in the spiral structure of a gravitationally unstable disc (See fig. 1). This mechanism solves both the timescale and the mass problems, as it occurs rapidly and leads to the formation of planetary objects.

The fate of planetary cores in massive protostellar discs is still unknown. On one hand, a planetary object embedded into a gas disc tends migrate towards the central object. The rate of migration depends on the mass of the body: low mass planets move towards the central protostar very fast (type I migration, see fig. 2) while massive objects can open a gap, slowing down this process (type II migration, see fig. 2). On the other hand, the planetary core can accrete disc material, potentially undergoing runaway accretion (Pollack et al. 1996) and becoming a gaseous giant. The interplay between these two mechanisms ultimately determines the fate of the planetary cores.

After a preliminary analytical analysis of the problem, we will perform hydrodynamical SPH simulations of planet disc interaction, including migration and accretion onto the protoplanet. We will investigate under which conditions planetary cores are able to survive, forming gaseous giant planets. Finally, we will use a radiative transfer code to assess whether these mechanisms are observable with ALMA facilities.

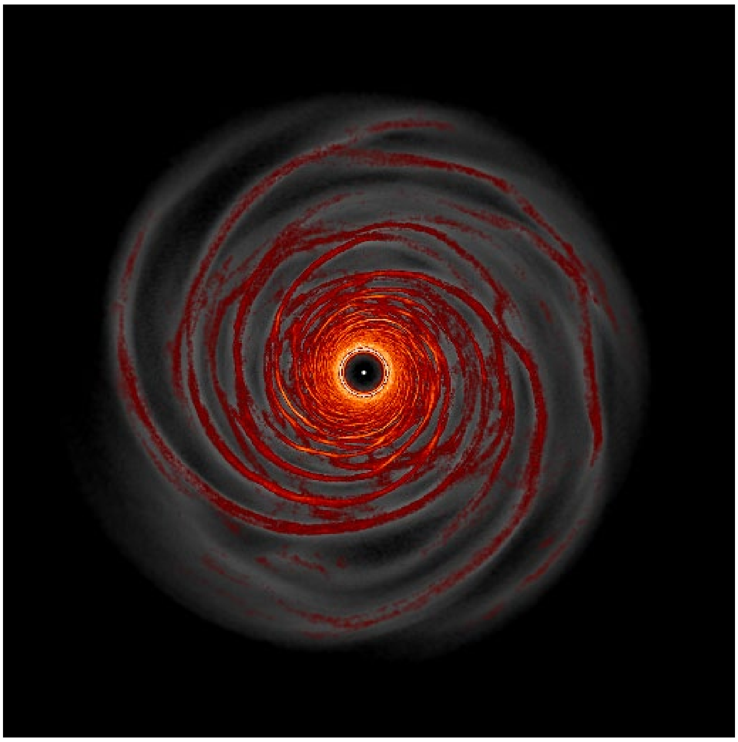

Figure 1.: Dust trapping in gas spiral arms. Snapshot of an SPH simulation of dust and gas in a gravitationally unstable protoplanetary disc, showing that dust particles (red region) are trapped inside gas spiral arms (grey background). Readapted from Longarini et al. 2023b. Solid particles concentration inside spiral arms is so high that the role of the self-gravity becomes important, and dust can possibly collapse, forming planetary cores. The aim of the project is to investigate the fate of these planetary cores.

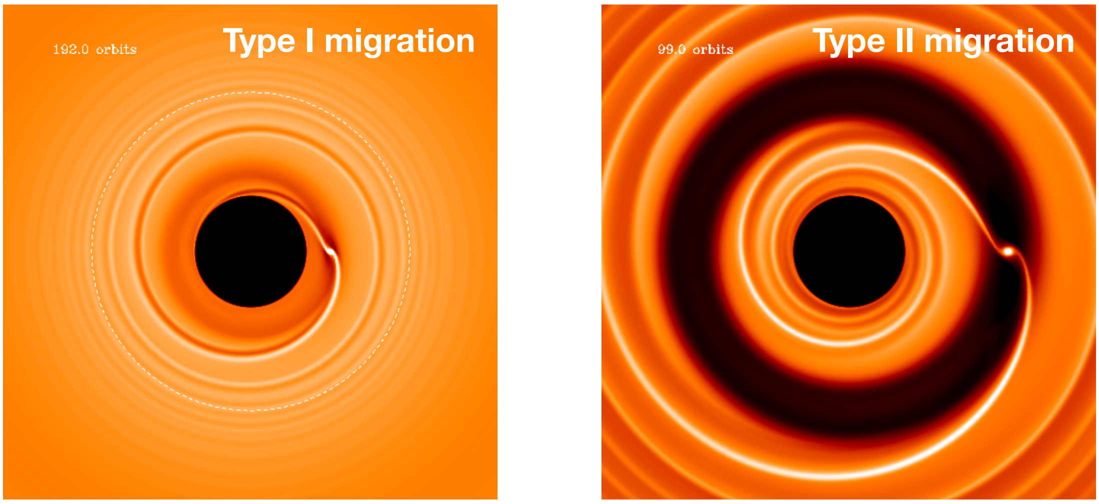

Figure 2.: Comparison between type I and type II planetary migration. (Credits to Frederic Masset).

Project Details

The student involved in this project will investigate the interplay between planetary cores migration and accretion in massive protostellar discs. This study would be important to determine if dust collapse in GI spirals is a viable way to form the embryos of Class II ALMA planets (Andrews et al. 2008, see fig.3) For this purpose, the student will:

- Analytically compute the migration and accretion timescale for a planetary core and compare them. Is there a realistic sweet spot for which planetary cores survive and become gas giants? What are the physical parameters involved?
- Perform global hydrodynamical simulation with the SPH code PHANTOM (Price et al. 2018) to test the aforementioned model and explore as much as possible the parameter space.
- Create synthetic ALMA observation of the previous simulations with the code MCFOST (Pinte et al. 2006, Pinte et al. 2009), investigating the possible presence of signatures of planet formation in young systems.
- Place the results in the broader context of the data derived from the ALMA large program DSHARP (Andrews at al. 2018, see fig. 3).

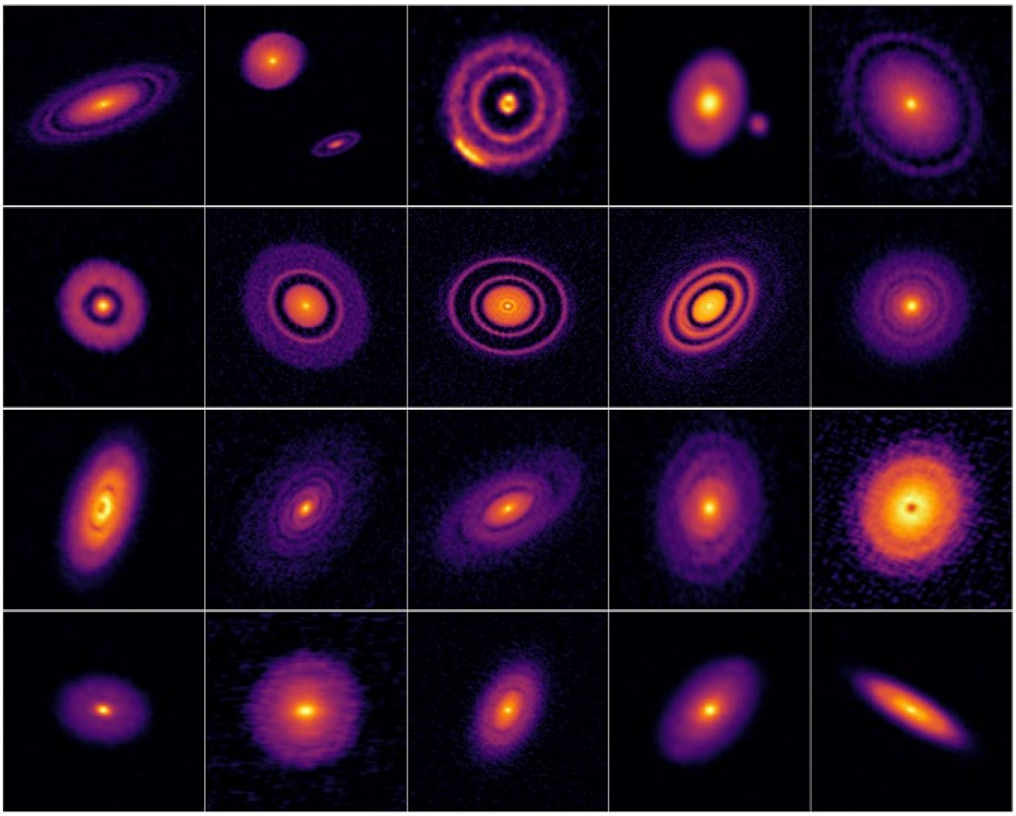

Figure 3.:High resolution dust continuum emission of the DSHARP large program sources (Andrews et al. 2018).

Skills Required

- The project will require programming in a language of the student’s choice (Python is preferable).
- A background of fluid dynamics, for example, the Part II course “Astrophysical fluid dynamics” is desirable.

Useful References (List of important papers/review articles relevant to the project)

- Armitage 2012, "Astrophysics of planet formation", Cambridge University Press.
- Rice et al. 2004, "Accelerated planetesimal growth in self-gravitating protoplanetary discs", Monthly Notices of the Royal Astronomical Society, Volume 355, Issue 2, pp. 543-552.
- Rice et al. 2006, "Planetesimal formation via fragmentation in self-gravitating protoplanetary discs", Monthly Notices of the Royal Astronomical Society: Letters, Volume 372, Issue 1, pp. L9-L13.
- D'Angelo & Lubow 2008, ""Evolution of migrating planets undergoing gas accretion", The Astrophysical Journal, Volume 685, Issue 1, pp. 560-583.
- Booth & Clarke 2016, "Collision velocity of dust grains in self-gravitating protoplanetary discs", Monthly Notices of the Royal Astronomical Society, Volume 458, Issue 3, p.2676-2693.
- Baehr & Zhu 2021, "Particle dynamics in 3D self-gravitating disks. I. Spirals", The Astrophysical Journal, Volume 909, Issue 2, id.135, 12 pp.
- Longarini et al. 2023, "The role of the drag force in the gravitational stability of a dusty planet-forming disc - II. Numerical simulations", Monthly Notices of the Royal Astronomical Society, Volume 522, Issue 4, pp.6217-6235.

General References (List of papers referred to in the project)

- Goldreich & Ward 1973, ""Formation of planetesimals", Astrophysical Journal, Vol. 183, pp. 1051-1062 (1973)
- Weidenschilling 1977, "Aerodynamics of solid bodies in the solar nebula", Monthly Notices of the Royal Astronomical Society, vol. 180, July 1977, p. 57-70.
- Boss 1997, "Giant planets formation by gravitational instability", Science, Vol. 276, p. 1836-1839 (1997).
- Pollack et al. 1996, "Formation of the giant planets by concurrent accretion of solid and gas", Icarus, Volume 124, Issue 1, pp. 62-85.
- Price et al. 2018, "PHANTOM: a smoother particle hydrodynamics and magnetohydrodynamics code for astrophysics", Publications of the Royal Astronomical Society of Australia, Volume 35, id.e031, 82 pp.
- Andrews et al. 2018, "The Disk Substructures at High Angular Resolution Project (DSHARP). I. Motivation, Sample, Calibration, and Overview", The Astrophysical Journal Letters, Volume 869, Issue 2, id. L41, 15 pp.
- Pinte et al. 2006, “Monte Carlo radiative transfer in protoplanetary disks”, Astronomy and Astrophysics, Volume 459, Issue 3, December I 2006, pp.797-804
- Pinte et al. 2009, “Benchmark problems for continuum radiative transfer. High optical depths, anisotropic scattering, and polarisation”, Astronomy and Astrophysics, Volume 498, Issue 3, 2009, pp.967-980

Project 15: Unveiling Black Hole Accretion in Dwarf Galaxies

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UTO: Debora Sijacki (deboras@ast.cam.ac.uk)

Project Summary

This project aims to enhance our understanding of black hole (BH) accretion in dwarf galaxies by utilising state-of-the-art cosmological zoom-in simulations of individual dwarf galaxies and conducting a comparative analysis of different models onto BHs. Thanks to novel refinement techniques we can capture gas flows onto the BH in exquisite detail, which will allow us to better model the accretion physics. The results from these simulations will then be compared with observational constraints across a range of redshifts to refine the models and develop next generation accretion prescriptions that can be applied to the whole galaxy mass range.

Background

Massive BHs are seeded at high redshift and grow over cosmic time via merging with each other and accretion of material. As BHs accrete material they can release vast amounts of energy in the form of jets and winds that plays an important role in shaping the evolution of galaxies (e.g., Binney & Tabor 1995; Di Matteo et al. 2005; Bower et al. 2006; Croton 2006; Sijacki et al. 2007; Cattaneo et al. 2009). This energy release, known as feedback, is a well-established mechanism for the regulation of star formation in galaxy formation theory. However, the understanding of BH accretion and feedback processes in dwarf galaxies remains limited. This Part III project aims to shed light on the intricate interplay between AGN and dwarf galaxies, employing cosmological zoom-in simulations and observational constraints.

Traditionally, the expectation was that BHs would have a limited impact on dwarf galaxy properties and instead feedback from supernovae (SN) would be the dominant mechanism to regulate star formation in such systems (e.g., Dekel & Silk 1986). This is seen in a number of cosmological simulations (e.g., Dubois et al. 2015; Beckmann et al. 2017; Habouzit et al. 2017; Trebitsch et al. 2018), however, such simulations employ simplistic models for BH accretion, namely the Bondi model, which has a strong dependence on BH mass and by definition inhibits BH growth in low mass systems. Therefore, by construction SN feedback has had to “pick up the slack”. While the Bondi model is conceptually simple, it relies on a number of assumptions that are often violated in reality, leaving scope for more physically motivated modelling of BH accretion in cosmologically relevant environments. Additionally, it has been demonstrated that there are sufficient amounts of gas in dwarfs for efficient BH growth (e.g., Sharma et al. 2022, Koudmani et al. 2022, Wellons et al. 2023). Therefore, this project aims to explore alternative accretion models that don’t penalise the growth of low mass BHs in dwarf galaxies to fully explore their potential in shaping galactic properties.

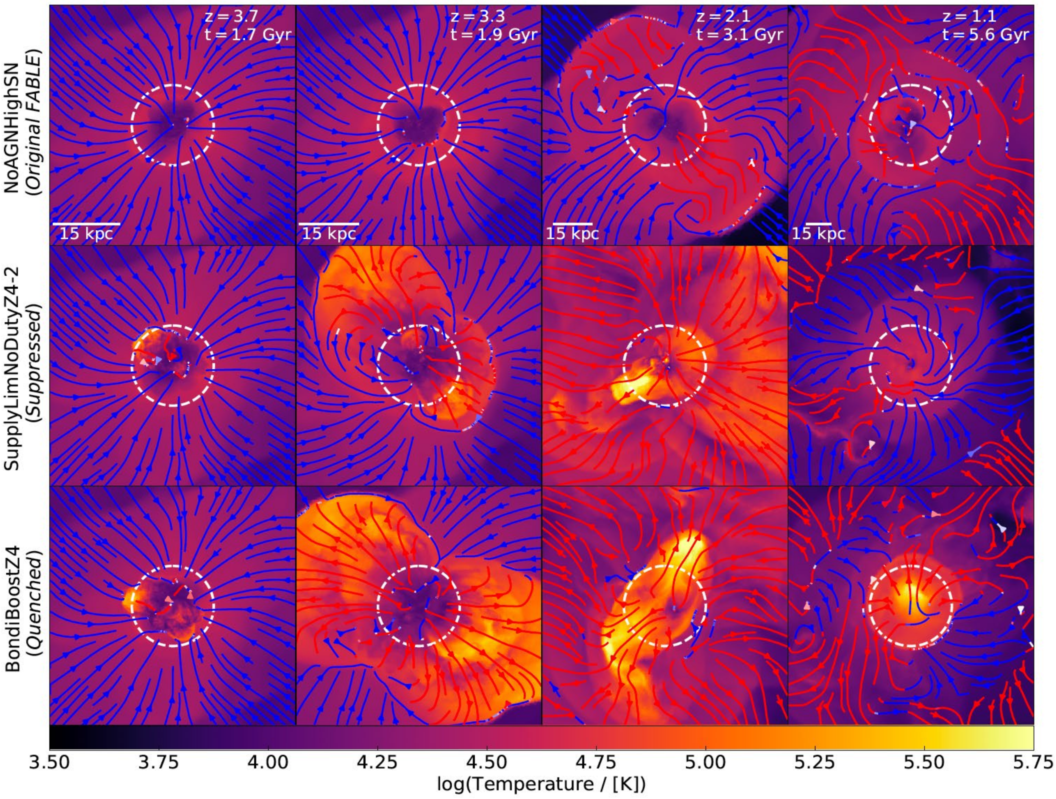

Figure 1.: Temperature projection maps of dwarf galaxies simulated over cosmic time from Koudmani et al 2022. The rows compare when the galaxy has no BH feedback (top), supply limited accretion (middle) and a boosted Bondi model (bottom), while from left to right the systems evolve with time (as labelled). Velocity fields are shown by the blue and red streamlines. Not only do the accretion models affect the growth rate of the BHs but also the levels of feedback, with strong, hot outflows being generated in the cases with BHs. This Part III project will compare Bondi models to a sink accretion model that has previously not been considered in such simulations.

Project Details

The project will employ cosmological zoom-in simulations performed with the moving mesh code AREPO (Springel 2010), which combine the advantages of high-resolution simulations with a realistic cosmological context. This technique allows for the detailed study of the formation and evolution of dwarf galaxies, including the accretion processes onto the central BH. The student will be supplied with a set of pre-run cosmological zoom-in simulations (although they will be the first to analyse them) where the BH is accreting either at the Bondi rate or based on the sink-particle-method. Initially the focus will be on the analysis of these simulations, with the possibility for the student to perform additional simulation runs to explore further accretion models, if sufficient progress is made and time permits.

- Investigate and quantify BH accretion processes in dwarf galaxies using state-of-the-art cosmological zoom-in simulations.
- Compare and contrast different models, including the sink-particle scheme and Bondi accretion, to understand their effectiveness in growing black holes in low-mass systems.
- Assess the validity and reliability of these accretion models through a comprehensive analysis of observational constraints on AGN activity in dwarf galaxies, from local constraints to the latest high-redshift measurements from JWST. This could include comparing to X-ray properties (Birchall et al. 2020; Mezcua et al. 2018), MaNGA IFU observations (Mezcua & Domínguez Sánchez 2020) and/or AGN outflow properties (Liu et al. 2020; Aravindan et al. 2023).

Skills Required

- The student should be keen on programming and have a basic knowledge of C and good knowledge of Python.
- The Part II courses “Astrophysical Fluid Dynamics” and “Cosmology” are required.

Useful References (List of important papers/review articles relevant to the project)

- Koudmani S., Sijacki D., Smith M. C., 2022, MNRAS, 516, 2112
- Sharma R. S., Brooks A. M., Tremmel M., Bellovary J., Ricarte A., Quinn T. R., 2022, ApJ, 936, 14
- Wellons S., et al., 2023, MNRAS, 520, 5394

General References (List of papers referred to in the project)

- Aravindan A., Liu W., Canalizo G., Veilleux S., Bohn T., Sexton R.~O., Rupke D.~S.~N., et al., 2023, ApJ, 950, 33
- Beckmann R. S., et al., 2017, MNRAS, 472, 949
- Binney J., Tabor G., 1995, MNRAS, 276, 663
- Birchall K. L., Watson M.~G., Aird J., 2020, MNRAS, 492, 2268
- Bower R. G., Benson A. J., Malbon R., Helly J. C., Frenk C. S., Baugh C. M., Cole S., Lacey C. G., 2006, MNRAS, 370, 645
- Cattaneo A., et al., 2009, Nature, 460, 213
- Croton D. J., 2006, MNRAS, 369, 1808
- Dekel A., Silk J., 1986, ApJ, 303, 39
- Di Matteo T., Springel V., Ilernquist L., 2005, Nature, 433, 604
- Dubois Y., Volonteri M., Silk J., Devriendt J., Slyz A., Teyssier R., 2015, MNRAS, 452, 1502
- Habouzit M., Volonteri M., Dubois Y., 2017, MNRAS, 468, 3935
- Liu W., Veilleux S., Canalizo G., Rupke D.~S.~N., Manzano-King C.~M., Bohn T., U V., 2020, ApJ, 905, 166
- Mezcua M., Civano F., Marchesi S., Suh H., Fabbiano G., Volonteri M., 2018, MNRAS, 478, 2576
- Mezcua M., Dom{\'\i}nguez S{\'a}nchez H., 2020, ApJL, 898, L30
- Sijacki D., Springel V., Di Matteo T., Hernquist L., 2007, MNRAS, 380, 877
- Springel V., 2010, MNRAS, 401, 791
- Trebitsch M., Volonteri M., Dubois Y., Madau P., 2018, MNRAS, 478, 5607

Project 16: Investigating the impact of point-source masking on cluster cosmology with the Sunyaev-Zeldovich effect

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UTO: Anthony Challinor (a.d.challinor@ast.cam.ac.uk)

Project Summary

The abundance of galaxy clusters as a function of mass and redshift is a powerful cosmological probe from which fundamental information about the Universe can be inferred. Galaxy clusters can be detected from observations at mm wavelengths through the imprint they leave on the cosmic microwave background (CMB) via the thermal Sunyaev-Zeldovich (tSZ) effect. These tSZ-detected clusters can, in turn, be used for cosmological inference, for which the observed cluster abundance has to be accurately modelled. When clusters are detected in mm maps, bright point sources are typically masked before the detection algorithm is applied, as they can lead to spurious detections. However, many of these point sources correspond to galaxies, some of which may reside in clusters. Therefore, masking point sources may lead to fewer detected clusters relative to the case in which the mask is uncorrelated with the cluster population, which is what is typically assumed. If unaccounted for, this effect may bias cosmological inference. This project aims to quantify the magnitude of this effect and to assess its impact on number-count cosmological constraints in the context of current and upcoming tSZ cluster surveys.

Background

The abundance of galaxy clusters, the largest gravitationally bound objects in the Universe, as a function of mass and redshift is a powerful cosmological probe, sensitive to a number of cosmological parameters and models (see Allen et al. 2011 and Kravtsov & Borgani 2012). This cosmological information can be extracted by comparing the observed cluster abundance, as obtained through X-ray, optical, or mm observations, to its theoretical prediction, in what are known as “cluster number-count” analyses (see, e.g., Zubeldia & Challinor 2019 for an example).

In mm observations, which are the focus of this project, clusters can be detected via the imprint they leave on the CMB through the thermal Sunyaev-Zeldovich (tSZ) effect. The tSZ effect is a spectral distortion of the CMB spectrum that occurs when (very cold) CMB photons go through the very hot, ionised gas that fills the intra-cluster medium (ICM). Some of these photons interact with the ICM electrons via inverse Compton scattering and are, on average, upscattered towards higher energies, leading to a small distortion of the CMB blackbody around the locations of clusters in the sky. By searching for this distortion, clusters can be detected in a blind way from the data (see, e.g., Zubeldia et al. 2021).

Before the application of a tSZ cluster detection algorithm, bright point sources are typically masked, as they can lead to spurious detections. This is often done by cutting out a small region in the observed maps around the sky location of each point source, discarding the data within it. The key observable to be predicted in a cluster count analysis is the number of detected clusters (the "cluster abundance") as a function of mass and redshift. If the point-source mask is uncorrelated with the cluster population, the observed cluster abundance is simply given by the predicted abundance for the full survey area, which can be computed for a given detection algorithm, multiplied by the fraction of the survey area that is not masked out by the point-source mask. In tSZ surveys, however, many of the bright point sources that are masked correspond to galaxies, some of which may reside in clusters. Therefore, the mask may be significantly correlated with the cluster population, which means fewer clusters may be detected relative to the case in which the mask and the cluster population are uncorrelated. If unaccounted for, this effect may, in turn, lead to biases in number-count cosmological analyses, as the predicted abundance may not match the observed one at a statistically significant level. This project aims to quantify the magnitude of this effect in the context of current tSZ surveys and to assess its impact on number-count cosmological constraints, developing approaches to model it properly if its impact is found to be significant.

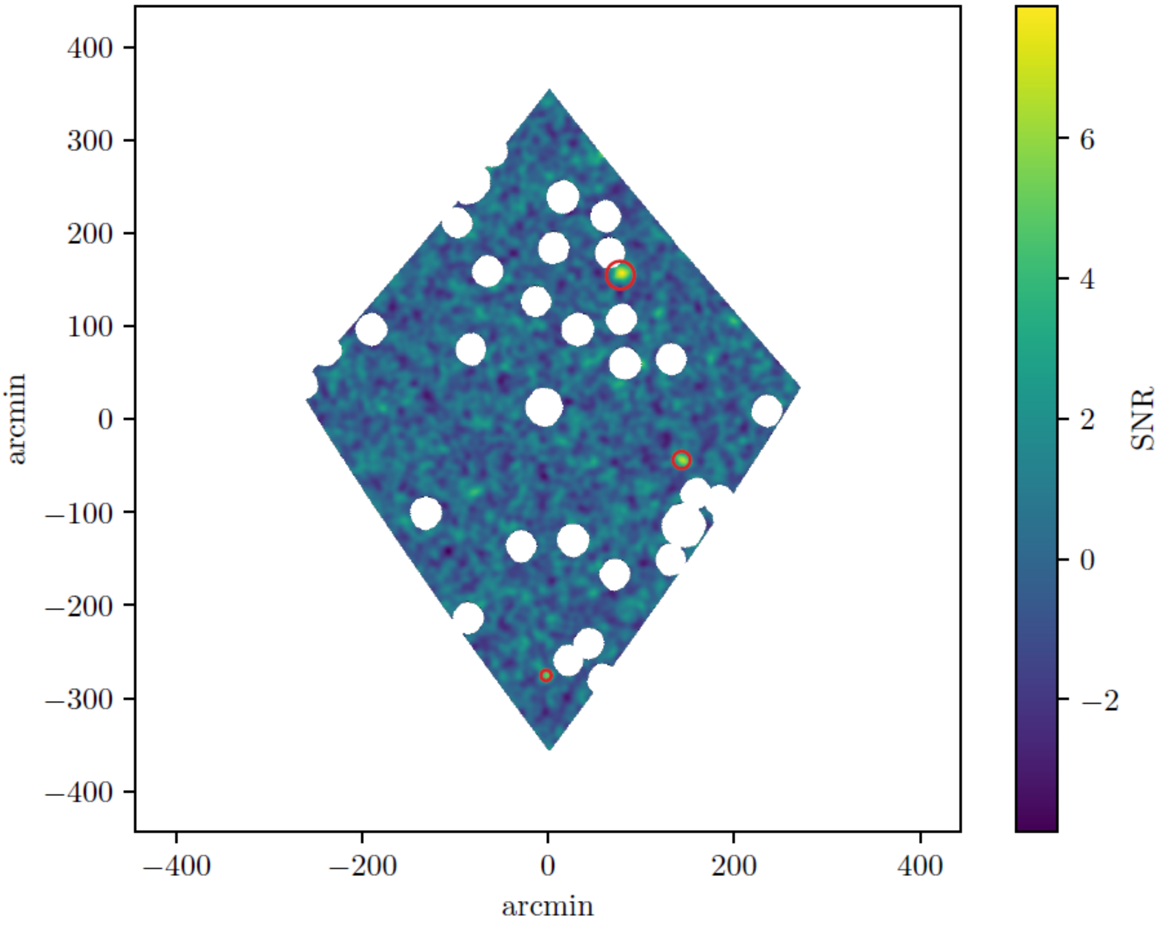

Figure 1.: Galaxy cluster signal-to-noise (SNR) map for a small part of the sky produced with the SZ cluster-finding code SZiFi (Zubeldia et al. 2022) using data from the Planck observatory. The red circles correspond to detections with SNR > 5 and the white circles to the point-source mask, which may be correlated with the underlying cluster population.

Project Details

After absorbing the relevant background literature, you will estimate numerically the number of additional “missed detections” due to the point-source mask for the Planck, ACT, and SPT tSZ cluster surveys. You will do this as a function of cluster mass and redshift. As a proxy for the underlying cluster population, you will use existing cluster catalogues constructed from optical and X-ray observations, as they are expected to be uncorrelated with the tSZ point-source mask; accurate modelling of the relevant optical and X-ray selection functions will be necessary. You will then assess the impact of these additional missed detections on the number-count cosmological constraints derived from the cluster catalogues of the tSZ surveys considered. You will do this using the cnc cluster number-count theory code, a Python package developed by the primary project supervisor. If the impact is found to be significant, you will investigate possible approaches to model properly the effect of a correlated point-source mask, implementing the one that is found to be most effective in cnc. Finally, time permitting, you will produce forecasts for the magnitude of this effect for two upcoming observatories that are set to revolutionise cluster cosmology: the Simons Observatory and CMB-S4.

Skills Required

- Good programming skills, with knowledge of Python, and basic notions of statistics.
- Familiarity with the material covered in the Part II Introduction to Cosmology course and the Part III Cosmology course is advisable.

Useful References (List of important papers/review articles relevant to the project)

- Allen, Evrard & Mantz, 2011. Cosmological parameters from observations of galaxy clusters. arXiv: 1103.4829.
- Kravtsov & Borgani, 2012. Formation of galaxy clusters. arxiv:1205.5556.
- Zubeldia, Rotti, Chluba & Battye, 2022. Galaxy cluster SZ detection with unbiased noise estimation: an iterative approach. arxiv:2204.13780.

General References (List of papers referred to in the project)

- Zubeldia & Challinor, 2019. Cosmological constraints from Planck galaxy clusters with CMB lensing mass bias calibration. arXiv: 1904.07887.

Project 17: Can we use the radial velocity technique to find planets around white dwarf stars?

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Supervisor III: Simon Hodgkin (sth@ast.cam.ac.uk)

UTO: Ian Parry (irp@ast.cam.ac.uk)

Project Summary

White dwarfs are the end state of stellar evolution for stars like our Sun, and there is substantial evidence that planetary systems exist around them: observations of planetary material 'polluting' the white dwarfs' surface, circumstellar dust, and gas discs, and even a handful of planet candidates (Figure 1). One of the most used techniques for discovering planets around main sequence stars is the radial velocity technique, where we measure the Doppler shift of the stars' spectral lines due to the presence of a planetary companion. This technique has always been thought to be difficult to use on white dwarf stars due to their intrinsic faint magnitudes, lack of spectral absorption lines, and broad spectral features. However, 'polluted' white dwarfs have narrow spectral lines on top of the broad H and He lines (Figure 2) and enable the possibility of obtaining precise radial velocities. This project will use spectroscopic data of polluted white dwarfs that spans up to 15 years. The student will investigate the best ways to obtain precise radial velocities for these stars, measure the radial velocities, and discover and constrain the parameter space of planets that could be discovered around these white dwarfs.

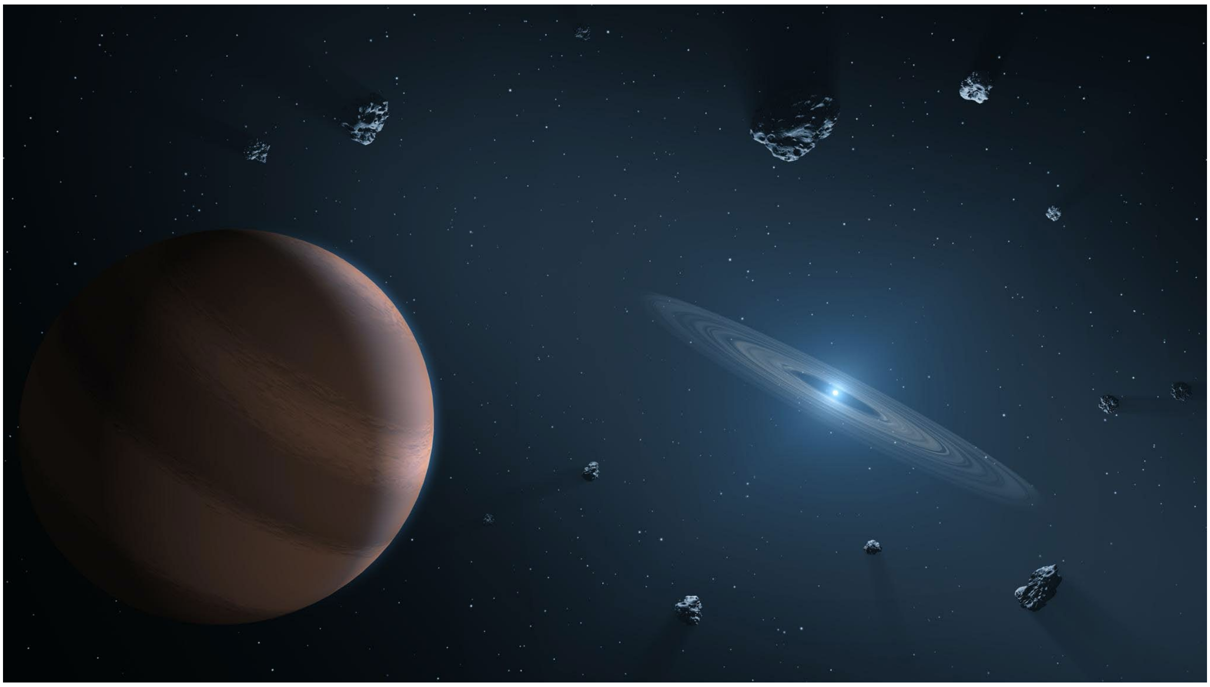


Figure 1.: An artist's impression of a polluted white dwarf system, where an asteroid is perturbed towards the white dwarf by an outer planet, it approaches the white dwarf, tidally disrupts into a disc, and subsequently accretes onto the white dwarf where we take spectroscopy to measure its bulk composition.

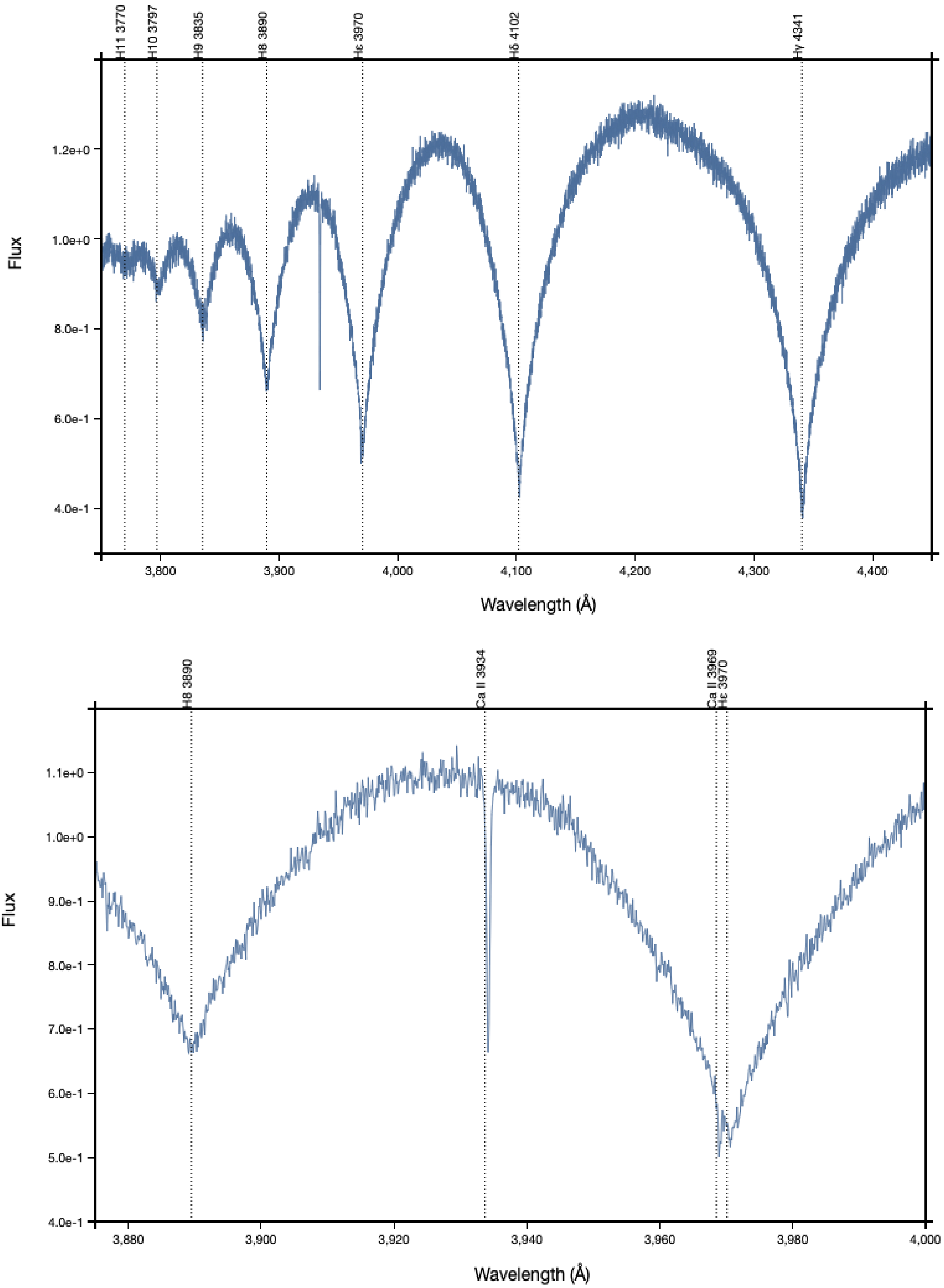


Figure 2.: Top: A spectrum of a hydrogen atmosphere white dwarf, G29-38, which is known to be polluted with heavy metals. The Hydrogen Balmer lines are marked - due to the strong surface gravity of white dwarfs these lines are broad. Bottom: A zoom in of the Calcium H and K lines in the spectra of G29-38, these calcium lines are from a planetary body that has ultimately ended up in the atmosphere of the white dwarf. The student will be fitting to these lines to see if there is a radial velocity shift in the wavelengths.

Background

Once a star, similar to our Sun, ceases fusing hydrogen, it will undergo a violent stage of stellar evolution resulting in the production of a small, hot and dense stellar core; this is a white dwarf. 97% of the Milky Way stars will end their life as white dwarfs. White dwarfs are used throughout astronomy, for example, as tracers of the history and dynamics of stellar populations in the Milky Way, laboratories to test theories of fundamental physics, and to study the bulk composition of exoplanetary material.

It has been demonstrated that although the inner planetary system is engulfed during the red giant stage, the outer planetary system can survive to the white dwarf phase. Evidence of this comes from observations of dust and gas discs surrounding a fraction of white dwarf stars and planetary material 'polluting' the atmospheres of white dwarfs (e.g., see review by Farihi 2016). Spectroscopic observations of polluted white dwarfs reveal the bulk composition of the planetary material accreted; this is the only way to directly measure the bulk composition of exoplanetary material (e.g., Klein et al. 2021).

Although it is thought that planets surviving in the outer system are common to explain these polluted white dwarfs, the discovery of planets around white dwarf stars is rare with only a handful of planet candidates existing (e.g., Vanderburg et al. 2019). This contrasts to main sequence stars where over 5000 planets have been discovered to date. The first exoplanet discovered around a main sequence star was via the radial velocity method (Mayor and Queloz, 1995, Figure 3) where they discovered a Jupiter mass planet around a sun-like star. This project aims to explore this method for white dwarf stars.

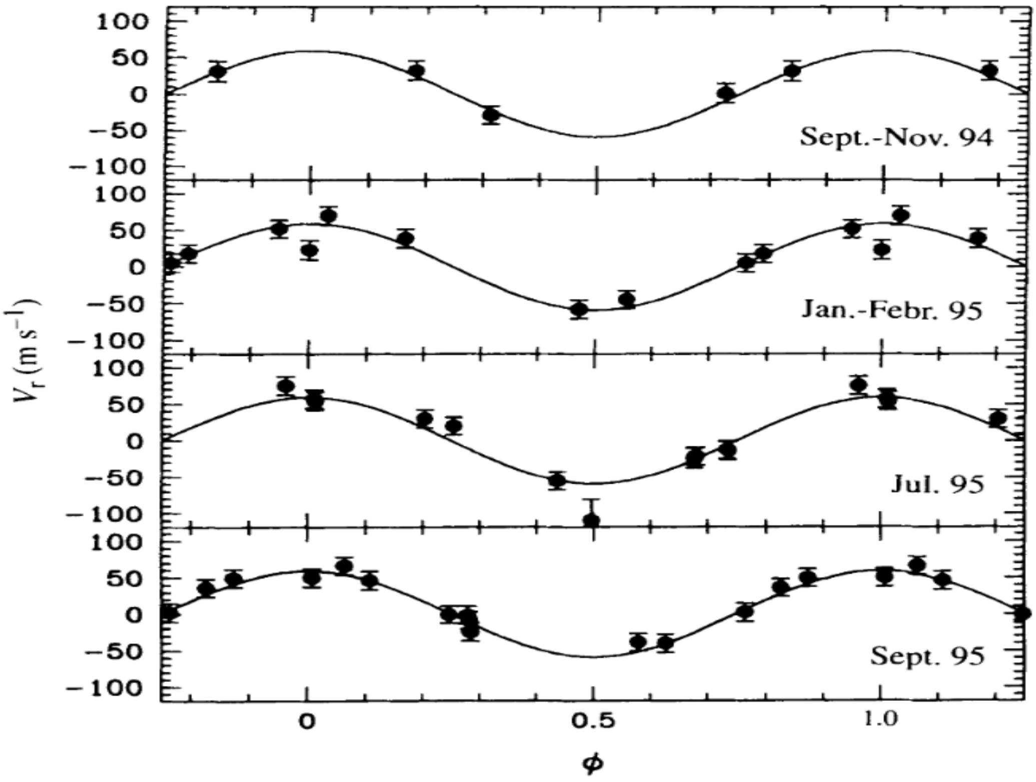


Figure 3.: The first radial velocity curves of a planetary mass body made by Mayor and Queloz (1995) of 51 Pegasi b. The planet has a mass of approximately 0.5 Jupiter masses on an orbit with a period of 4 days.

Project Details

The student will begin by simulating radial velocity curves for hypothetical white dwarf and planet systems and doing back of the envelope calculations to understand the required radial velocity precision needed to discover planets around white dwarf stars. The student will then investigate high resolution spectra of a sample of polluted white dwarfs taken over 15 years. The student will analyse each epoch of data to identify the metal lines from the polluting planetary material, fit these lines to measure the radial velocity of the spectra for that epoch using the narrow metal lines, and produce radial velocity curves as shown in Figure 3. From these curves the student will investigate what masses and orbital periods of planets are consistent and inconsistent with the data. The student will then explore different methods for obtaining radial velocities (see e.g., Section 6 of Hara and Ford, 2023) to investigate the best ways of using the radial velocity technique for polluted white dwarf stars.

Skills Required

- Basic python is preferable.
- Relevant courses:
    - Part II: Introduction to Astrophysics, Structure and Evolution of Stars
    - Part III: Extrasolar Planets: Atmospheres and Interiors and/or Exoplanets and Planetary Systems

Useful References (List of important papers/review articles relevant to the project)

- Gänsicke, B T., et al. "Accretion of a giant planet onto a white dwarf star." Nature 576.7785 (2019): 61-64.
- Klein, B L., et al. "Discovery of beryllium in white dwarfs polluted by planetesimal accretion." *The Astrophysical Journal* 914.1 (2021): 61
- Rogers et al. (2023) - currently in review, please email Supervisor I for a copy of the paper if interested.
- Vanderburg, A, et al. "A giant planet candidate transiting a white dwarf." Nature 585.7825 (2020): 363-367.

General References (List of papers referred to in the project)

- Farihi, J. "Circumstellar debris and pollution at white dwarf stars." *New Astronomy Reviews* 71 (2016): 9-34.
- Hara, N C., and Ford, E. B. "Statistical Methods for Exoplanet Detection with Radial Velocities." *Annual Review of Statistics and Its Application* 10 (2023): 623-649.
- Mayor, M, and Queloz, D. "A Jupiter-mass companion to a solar-type star." *Nature* 378.6555 (1995): 355-359.
- Vanderburg, A, et al. "A disintegrating minor planet transiting a white dwarf." *Nature* 526.7574 (2015): 546-549.
- Wright, Jason T., and B. Scott Gaudi. "Exoplanet detection methods." *arXiv preprint arXiv:1210.2471* (2012).

Project 18: Hunting for evidence of the first galaxies hidden in JWST data

Supervisor I: Callum Witten (cw795@cam.ac.uk)

Supervisor II: Hannah Übler (hu215@cam.ac.uk)

Supervisor III: Roberto Maiolino (rm665@cam.ac.uk)

UTO: Debora Sijacki (deboras@ast.cam.ac.uk)

Project Summary

Galaxies in the first 500 million years of the Universe (z>9) represent some of the earliest structures, however, the search for the very first population of galaxies ("Cosmic Dawn") continues. The JWST has unveiled a new era in observations of these first galaxies, revealing galaxies just 300 million years after the Big Bang (z~13), see Figure 1. However, even with the sensitivity of the JWST spectrograph NIRSpec, it is challenging to understand the properties of galaxies at this early time. By combining the spectra of galaxies at z>9, we can unveil their properties and start to constrain when galaxies started forming, placing constraints on the age-old question — when was "Cosmic Dawn"?

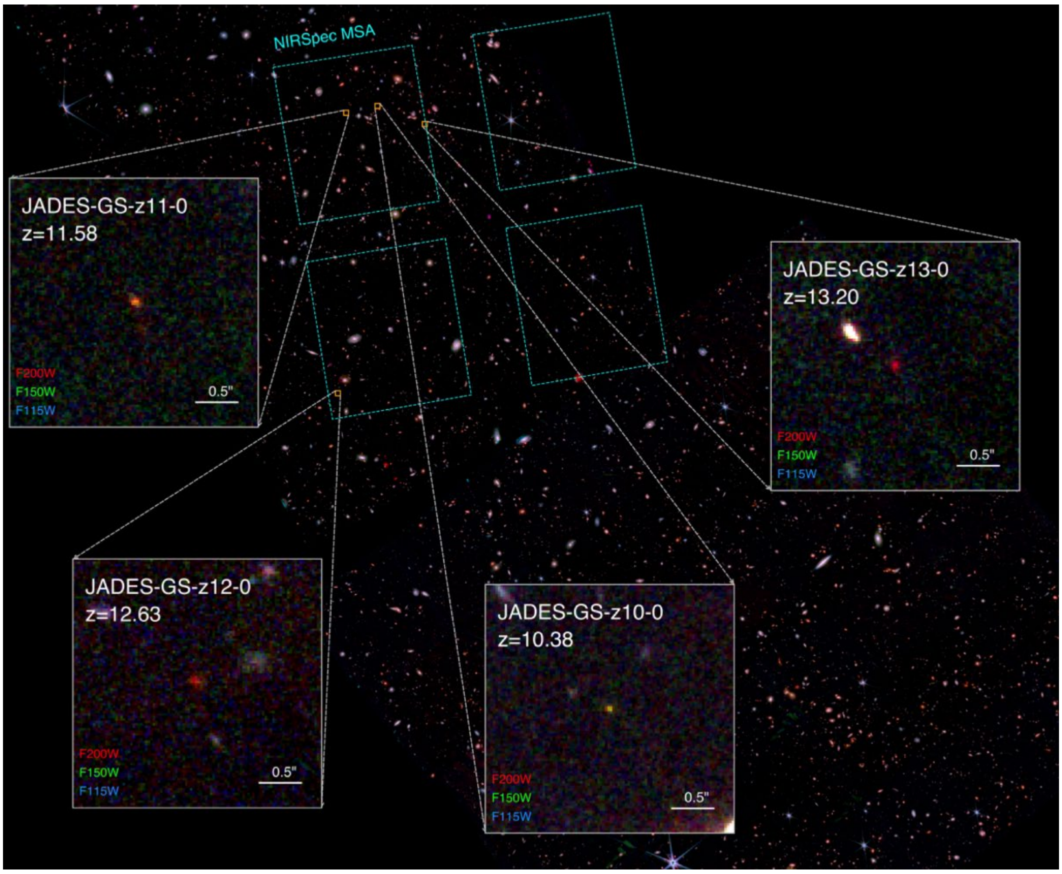


Figure 1.: Image from Robertson et al. 2023, showing pictures of the highest redshift galaxies ever detected.

Background

The hunt for “Cosmic Dawn” has been a long-standing quest of extragalactic astronomy. Direct observation of galaxies just 300 million years after the Big Bang has only become possible with the advent of JWST (Curtis-Lake et al. 2023, see Figure 2). Some indirect probes suggest galaxies could have formed significantly earlier than this (Hashimoto et al. 2018), while recent JWST observations suggest that galaxies at this epoch are metal-poor and therefore young (Curtis-Lake et al. 2023) potentially sign-posting this epoch as Cosmic Dawn. However, the question of whether these exciting early galaxies are indeed young or old can only be settled definitively with better data (see Figure 2 showing how weak the signal is when observing these early galaxies). Given, longer observations are very expensive, a key technique to increase the S/N in existing observations is to combine (“stack”) the spectra of galaxies in order to improve the signal and understand the properties of this early population of galaxies. Stacking observations has long been utilised with ground-based spectra (e.g., Witten et al. 2023) and is low-hanging fruit with JWST spectra.

One of the key diagnostics of the age of a galaxy is how metal enriched it is. The powerful radiation emitted by the first, young stars ionises their immediate surroundings (a region called the Stromgren sphere), which models predict are almost entirely composed of hydrogen and helium and hence are very metal-poor at these earliest times. As these first galaxies age, the stars within them evolve and create supernovae which enrich their host galaxy with metals such as Oxygen and Nitrogen. As new stars form in this enriched medium, their radiation excites the metal atoms that are now present, which in turn produce characteristic emission lines as these heavier elements relax to their ground states. The strength of these emission lines can hence be used to diagnose the amount of metal enrichment the galaxy has undergone. Given this process of metal enrichment is a function of time, we can use the presence or lack of emission lines in the stacked spectrum to understand how old these first galaxies are, thus placing constraints on when they formed and hence when Cosmic Dawn occurred.

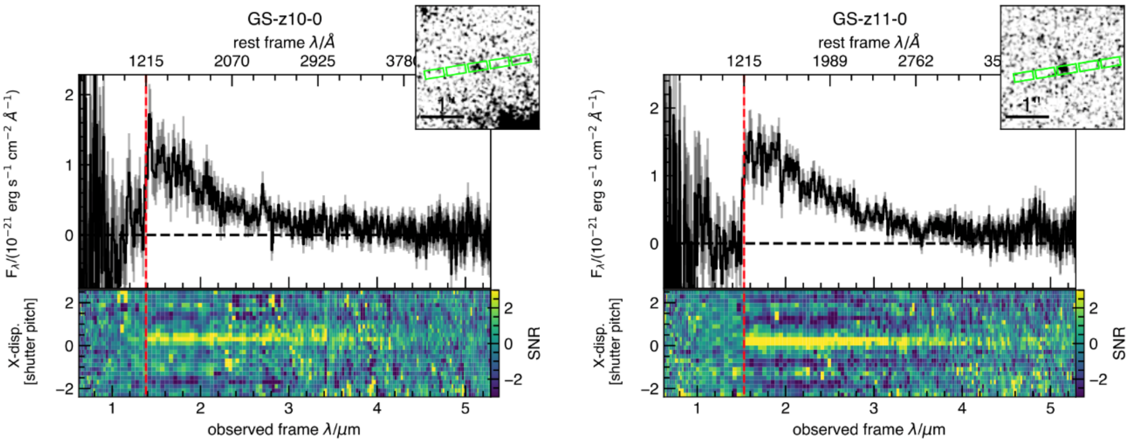


Figure 2.: Spectra from Curtis-Lake et al. 2023, showing the noise level of these observations, clearly too low S/N to constrain emission line fluxes or Balmer breaks.

Project Details

We will collect all existing JWST observations of galaxies (currently ~10 galaxies, see Harikane et al. 2023 for a nice summary of currently available spectra and for the data products) in the first 500 million years of the Universe (z>9). We will produce a code to optimally “stack” their spectra thus increasing the effective length of the observation and hence the signal from these galaxies. Stacking methods may involve continuum subtraction, object selection based on observed properties and bootstrapping. We will analyse their stacked spectrum to assess whether any emission lines become apparent (indicating the presence of metals, see Figure 3 for an example of a stack of emission-line galaxies) and whether indications of an old stellar population are clear. Both of these would indicate that galaxies formed at a much earlier time in the Universe's history. Alternatively, non-detections of both of these would indicate these galaxies are indeed very young. In the case of the former we can push back the time of Cosmic-Dawn to an earlier age in the Universe's history, in the latter case, we will show that these galaxies likely formed close to the epoch of observation and hence Cosmic Dawn likely occurred at a similar time. We will also attempt stacks of galaxies with specific properties to ascertain whether certain populations of galaxies are older than others. We will fit the stacked spectrum with a spectral energy distribution fitting tool (BAGPIPES) to place strong constraints on the stellar metallicity and age. A further extension to this project could be to use ensemble modelling of these spectra with BAGPIPES, assuming the sample have similar properties (eg. age, dust, UV slope), to better estimate the global properties of this population of galaxies.

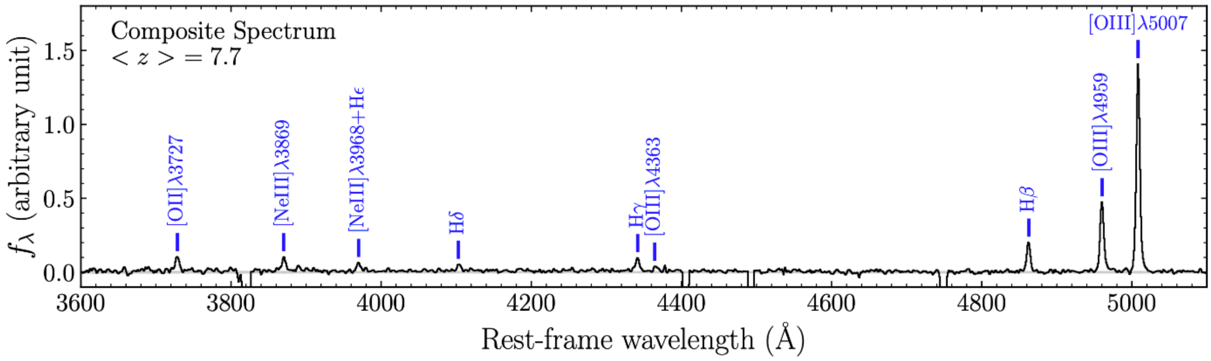


Figure 3.: An example of a stacked spectrum (Tang et al. 2023) of z~7 galaxies that show emission lines in their individual spectra. This stack reveals further faint emission lines, such as [OII] and [NeIII], that were not detected in the individual spectra of each galaxy. These galaxies are at a lower redshift compared to the sample this project will target. Moreover, these galaxies originally showed some emission lines (eg. Hb and [OIII]) in their individual spectra, which the sample this project will target do not.

Skills Required

- Experience with Python is desirable.
- Part attendance of Part II courses "Structure and Evolution of Stars", "Introduction to Astrophysics" and "Stellar Dynamics and Structure of Galaxies" is also desirable.

Useful References (List of important papers/review articles relevant to the project)

- https://en.wikipedia.org/wiki/List_of_the_most_distant_astronomical_objects (Introduction to high redshift galaxies)
- https://dawn-cph.github.io/dja/blog/2023/07/18/nirspec-data-products/ (Data products)
- Laporte, N. et al. 2021, MNRAS, 505, 3336–3346 (Old stellar populations)
- Harikane, Y. et al. 2020, ApJ, 902:117 (Stack of z~6 galaxies)

General References (List of papers referred to in the project)

- Robertson, B. et al. 2023, Nature Astronomy, Volume 7, p. 611-621

- Curtis-Lake, E. et al. 2023, Nature Astronomy, Volume 7, p. 622-632
- Hashimoto, T. et al. 2018, Nature, Volume 557, Issue 7705, p.392-395
- Witten, C. et al. 2023, ApJ, Volume 944, Issue 1
- Harikane, Y. et al. 2023, arXiv:2304.06658
- Tang, M. et al. 2023, arXiv:2301.07072

Project 19: Referenceless dual-field interferometry for the detection of giant planets.

Supervisor I: Mathias Nowak (mcn35@cam.ac.uk)

UTO: Mark Wyatt (wyatt@ast.cam.ac.uk)

Project Summary

The goal of this project is to determine to what extent dual-field interferometry without a phase-reference can be used to study giant exoplanets, and to adapt the tools developed during the ExoGRAVITY Large Program to this new technique. The project will involve manipulating interferometric data from the GRAVITY and MATISSE instruments obtained on the beta Pictoris exoplanetary system (fig. 1).

Figure 1.: Artist's impression of the giant planet beta Pictoris b orbiting around its star. Credits: ESO.

Background

Even though the temperature, atmospheric composition, and orbits of young giant planets hold crucial information on planet formation processes, only a handful of young giant planets have been detected so far, mostly with direct imaging instruments (SPHERE on the Very Large Telescope, or GPI on the Gemini telescopes), and at large separation from their stars (> 10 au). But the population of these young giants is expected to peak at smaller separations, closer to the H2O iceline.

Over the past few years, with the ExoGRAVITY Large Program, long-baseline interferometry with the GRAVITY instrument has started to make a significant contribution to the field, by providing extreme precision astrometric measurements, high-quality spectroscopy, and very high-contrast detections of some of these giant planets (GravityCollaboration 2019, 2020, Nowak et al. 2020, Hinkley et al. 2023, etc.). Long-baseline dual-field interferometry is now routinely used for the detection and study of giant exoplanets, but so far, all successful observations (beta Pic b and c, HR 8799 planets, etc.) have been obtained using dual-field phase-referenced interferometry in K-band with GRAVITY.

But new instruments are coming online, such as MATISSE (L-band, fig. 2) and possibly in the near future BIFROST (J-band). These instruments will offer a dual-field mode, but not the infrastructure required to phase-reference the observations to the central star. This has major consequences on how the observations can be reduced, and how the astrometry and spectroscopy can be extracted, raising the question of whether this referenceless dual-field mode will be as powerful as the phase-referenced dual-field mode of GRAVITY for the detection and study of giant planets.

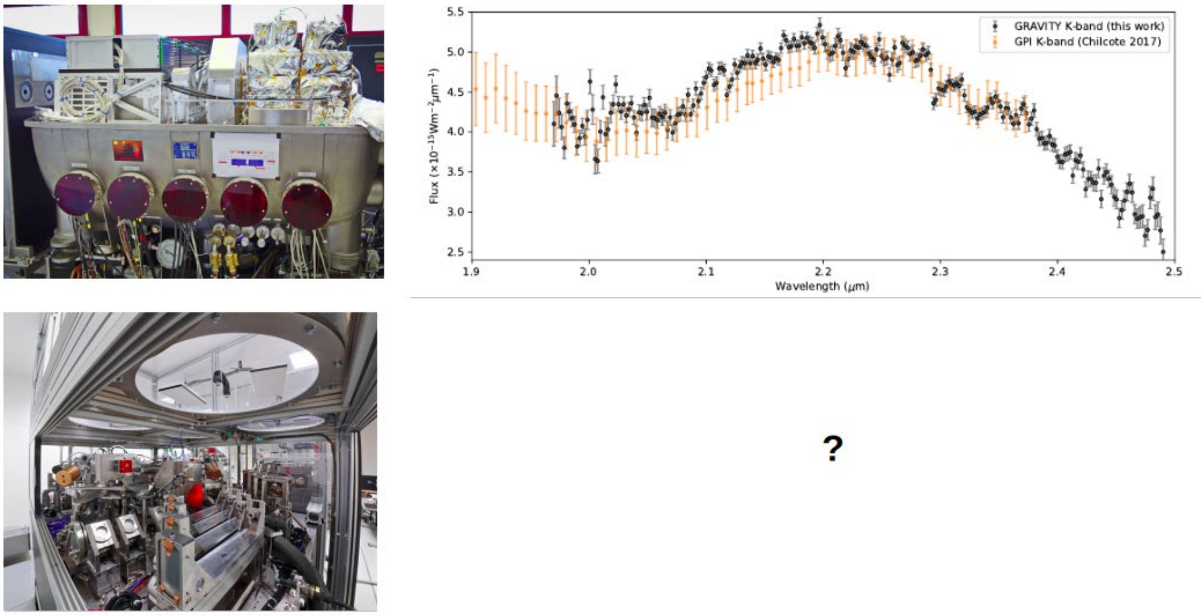


Figure 2.: A graphical representation of this project. Top panel: the GRAVITY instrument, which offers a phase-referenced dual-field mode in K-band is shown on the left, and the K-band spectrum extracted with it on the giant planet beta Pictoris b is shown on the right. Bottom pane: the MATISSE instrument, which offers a dual-field mode without a phase-reference in L-band is shown on the right. Can we get the missing L-band spectrum? Credits: ESO and Gravity Collaboration

Project Details

In this project, we will explore the difference between phase-referenced and referenceless high-contrast interferometric observations and determine how the data-reduction tools developed for GRAVITY can be adapted to the referenceless case.

Tests and development will be conducted using GRAVITY data from the ExoGRAVITY Large Program (K-band), and publicly available science verification data obtained with MATISSE (L-band) on the beta Pictoris system (see https://www.eso.org/sci/publications/announcements/sciann17548.html for more information on this dataset).

The first objective will be to develop tools to extract a K-band spectrum with GRAVITY without using the phase-referencing metrology system and use them on the MATISSE data to extract a L-band spectrum. The model currently used to extract the astrometry and spectroscopy of exoplanets from GRAVITY observations involves a combined fit with a model of the planet flux and a model of the leaking stellar flux, which always dominate the observation at these levels of contrast, the latter being properly phase-referenced to the star using a dedicated metrology system in the instrument. This model needs to be adapted to factor-in the lack of said metrology in instruments like MATISSE. This project will involve hands-on work with the data (understanding how they are structured, what they represent, how they have been acquired, etc.), developing a proper model to factor-in the missing phase-reference when fitting the exoplanet observations, and extracting K-band and L-band spectroscopy of a given target from GRAVITY and MATISSE data.

A possible second objective will be to determine to which point the additional fitting parameters introduced to compensate the lack of metrology hamper our ability to extract sub milli-arcsecond level astrometry.

Skills Required

- Programming in Python.
- Some understanding of optical interferometry would be an advantage.

Useful References (List of important papers/review articles relevant to the project)

- Nowak, M. et al "Direct confirmation of the radial-velocity planet β Pictoris c", A&A 642, L2 (2020)
- Gravity Collaboration et al. “First light for GRAVITY: Phase referencing optical interferometry for the Very Large Telescope Interferometer”, A&A 602, A94 (2017)
- Lopez B., Lagarde S., Petrov R. G., Jaffe W. et al. "MATISSE, the VLTI mid-infrared imaging spectro-interferometer", A&A 659, 192 (2022)

General References (List of papers referred to in the project)

- Gravity Collaboration et al. “First direct detection of an exoplanet by optical interferometry; Astrometry and K-band spectroscopy of HR8799 e”, A&A 623, L11 (2019)
- Gravity Collaboration et al. “Peering into the formation history of β Pictoris b with VLTI/GRAVITY long-baseline interferometry”, A&A 633, A110 (2020)
- Lacour, S. et al. "The ExoGRAVITY project: using single mode interferometry to characterise exoplanets", Proceedings Volume 11446, Optical and Infrared Interferometry and Imaging VII; 114460O (2020)

Project 20: Measurements of the dust distribution around galaxies and implications for large-scale cosmological structure statistics

Supervisor I: Niall MacCrann (nm746@cam.ac.uk)

Supervisor II: Blake Sherwin (bds30@cam.ac.uk)

UTO: Blake Sherwin (bds30@cam.ac.uk)

Project Summary

As we know from our own galaxy, cosmic "dust", populates interstellar space. Menard 2010 made a novel measurement of the projected dust profile around SDSS galaxies, by using the fact that the light from high redshift quasars experiences extinction, a wavelength-dependent suppression in brightness, due to this dust. They compare the dust profile to the matter profile, measuring the latter via the wavelength-independent change in brightness due to lensing magnification. In this project we will update these measurements to more recent datasets and study the implications of this extra-galactic dust extinction on various large-scale structure statistics such as galaxy clustering and galaxy-lensing cross-correlations. We will investigate biases in cosmological inference and whether there is interesting cosmological information in the measurements themselves.

Background

We can constrain the Universe's cosmological model (including e.g., the sum of the neutrino masses) using various statistics of the Universe's large-scale structure, as traced by galaxies. Combining information from galaxy surveys and CMB experiments can also be extremely powerful, with our group having specific expertise in both galaxy and CMB lensing science. We have recently led the state-of-the-art Atacama Cosmology Telescope CMB lensing analysis (https://arxiv.org/abs/2304.05202, https://arxiv.org/abs/2304.05196), resulting in large maps of the projected matter distribution that can be cross-correlated with galaxies.

As we work with exciting, statistically powerful new datasets, we must ensure systematic biases are under control. Small effects, such as the dust extinction described above may become important and should be characterised and perhaps included in models during cosmological inference.

Project Details

The initial steps in this project can take either an observational or theoretical direction. One option is that the student updates the measurements of Menard 2010 with more recent galaxy samples (e.g., the unWISE sample that has been used for several powerful recent cosmology analyses), and also using updated quasar samples. This has not been done to date – perhaps because large-scale structure analyses have been reluctant to consider this systematic effect, instead hoping it is negligible for current data.

This would be a great way to learn about the type of statistics we use in cosmology (e.g., correlation functions and power spectra), and how they are measured, as well as important physical effects like gravitational lensing.

A more theoretical direction would be to take the constraints from Menard et al. and construct a halo model, which could be used to predict the impact of extragalactic dust extinction on various large-scale structure statistics, and thus the importance for cosmological inference from these statistics. While Fang et al. 2011 studied the expected impact of dust extinction on some galaxy clustering statistics (BAO and RSD), the impact on other large-scale structure statistics such as those used in combined galaxy clustering and lensing analyses (which better constrain the dark matter clustering amplitude, and will be very widely used in the DESI / Rubin / Simons Observatory era) has not been investigated. We believe with the improved precision of current and upcoming data, dust extinction may become an important systematic effect.

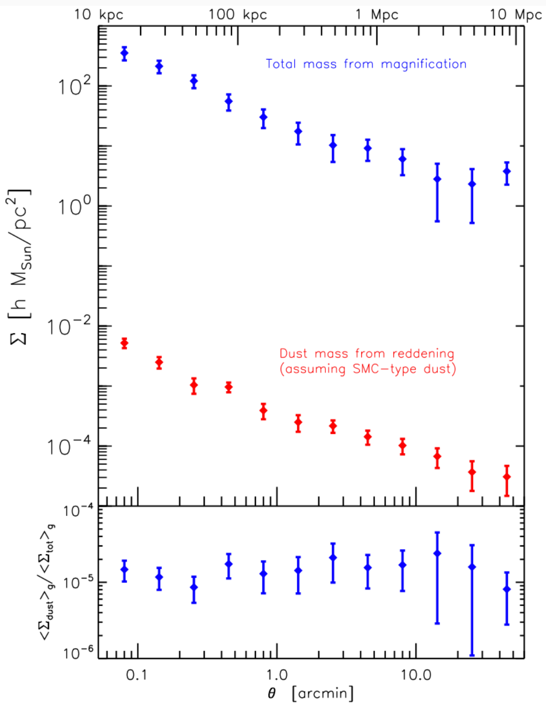


Figure 8. Correlation between magnification and galaxy overdensity as a function of scale. On scales smaller than $\sim$ 500 h^{-1} kpc, this quantity is a direct estimate of the mean surface density of galaxies (with $i < 21$).

Figure 1.: Figure from Menard 2010 showing the measurement of dust mass profile and total mass profile.

Skills Required

- Part III cosmology course
- Experience coding in python (or similar)
- Measuring and making theoretical predictions for cosmological power spectra (using existing public codes)
- An interest in large-scale structure cosmology and/or astrophysics of galaxies.

Useful References (List of important papers/review articles relevant to the project)

- https://arxiv.org/abs/0902.4240

General References (List of papers referred to in the project)

- https://arxiv.org/abs/2105.13548
- https://arxiv.org/abs/2303.08752
- https://arxiv.org/abs/1105.3421

Project 21: Lithium Production in Stars

Supervisor I: Christopher Tout (cat@ast.cam.ac.uk)

UTO: Christopher Tout (cat@ast.cam.ac.uk)

Project Summary

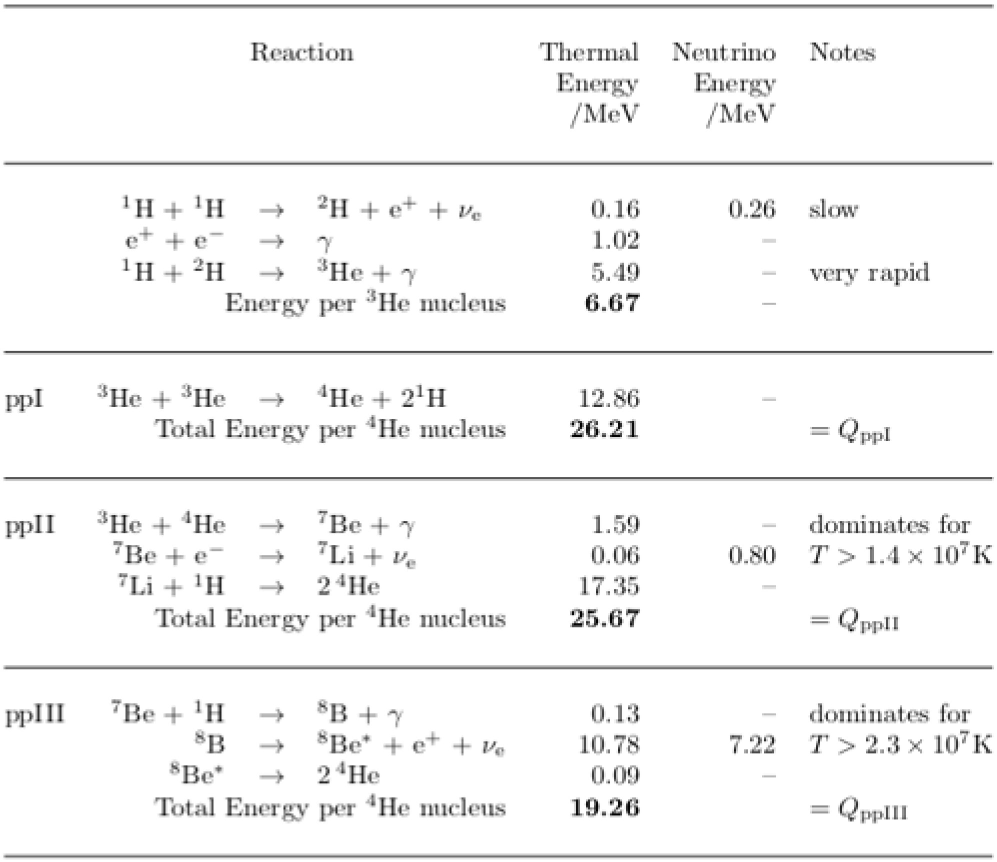
In this project you will investigate how lithium can be produced in stars by the Cameron-Fowler mechanism (Cameron & Fowler 1971). The process can take place at various stages in a star's life, but stellar models disagree on how efficient it is. Much of the uncertainty lies in the way the equations for nuclear fusion are coupled with those of diffusion. To investigate you will construct and compare various models based on different assumptions.

Background

Hot hydrogen fusion by the ppII chain (see Figure 1) has the potential to create lithium. However, at typical temperatures the lithium very quickly captures a proton and is destroyed. Equilibrium abundances are tiny, much smaller than observed in some giant stars. Cameron (1955) proposed that in a convective region beryllium-7 created in the branching reaction could be carried to cooler regions before decaying to lithium-7 and capturing a proton. Cameron & Fowler (1971) went on to argue that hot bottom burning at the base of the convective envelopes of asymptotic giant branch (AGB) stars could then be the source of an observed lithium enhancement in some early AGB stars. The process has been included in a number of stellar evolution codes (see for example Lau et al. 2012) but the critical interplay between burning and mixing makes the lithium production rate dependent on the modelling of the mixing and the numerical method used to implement it. This modelling also feeds back on the structure of the star so that is difficult to differentiate the cause of variations. The purpose of this project is to examine burning and mixing models in isolation from stellar structure to understand better the effects of physical and numerical differences on lithium production. In particular we are interested in how lithium production is affected when convection is modelled as a diffusive or advective process. The latter can be mimicked with a two-stream model such as that devised by Canon (1993).

Project Details

The project consists of writing code to solve the differential equations governing the pp chain reactions alongside those for mixing. The first step is to set up the nuclear reaction network, obtaining up to date reaction rates from recent literature. Initially the fusion network can be tested at fixed temperature and density to reproduce typical equilibrium abundances of isotopes in radiative, convectively stable, stellar material, a case which can be calculated analytically. The next step will model a convective region above the burning region into which the burning material mixes. You will investigate different rates of convection with three different numerical models, instantaneous mixing, diffusion, and advection, each with different mixing rates.



	Reaction	Thermal Energy /MeV	Neutrino Energy /MeV	Notes
	$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$	0.16	0.26	slow
	$\mathrm{e}^{+} + \mathrm{e}^{-} \rightarrow \gamma$	1.02	–	
	$^{1}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$	5.49	–	very rapid
	Energy per ^{3}He nucleus	**6.67**	–	
ppI	$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,{}^{1}\mathrm{H}$	12.86	–	
	Total Energy per ^{4}He nucleus	**26.21**		$= Q_{\mathrm{ppI}}$
ppII	$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$	1.59	–	dominates for
	$^{7}\mathrm{Be} + \mathrm{e}^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_{\mathrm{e}}$	0.06	0.80	$T > 1.4 \times 10^{7}\,\mathrm{K}$
	$^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow 2\,{}^{4}\mathrm{He}$	17.35	–	
	Total Energy per ^{4}He nucleus	**25.67**		$= Q_{\mathrm{ppII}}$
ppIII	$^{7}\mathrm{Be} + {}^{1}\mathrm{H} \rightarrow {}^{8}\mathrm{B} + \gamma$	0.13	–	dominates for
	$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$	10.78	7.22	$T > 2.3 \times 10^{7}\,\mathrm{K}$
	$^{8}\mathrm{Be}^{*} \rightarrow 2\,{}^{4}\mathrm{He}$	0.09	–	
	Total Energy per ^{4}He nucleus	**19.26**		$= Q_{\mathrm{ppIII}}$

Figure 1.: The reactions of the proton-proton chains. The ppI chain dominates at low temperatures, with ppII branching off at its last step and ppIII at the second step of ppII at sufficiently high temperatures. ^{7}Li is created by the ppII chain.

Skills Required

- Ability to set up differential equations and solve them numerically.

Useful References (List of important papers/review articles relevant to the project)

- Cameron A. G. W., Fowler W. A., 1971, ApJ, 164, 111
- Cannon, R. C., 1993, MNRAS, 263, 817

General References (List of papers referred to in the project)

- Cameron A. G. W., 1955, ApJ, 121, 144
- Lau H. H. B., Doherty C. L., Gil-Pons, P., Lattanzio J. C., 2012, Mem. S. A. It. Suppl., 22, 247

Project 22: Precision modelling of the hydrogen 21-cm signal from cosmic dawn and the epoch of reionization

Supervisor I: Anastasia Fialkov (afialkov@ast.cam.ac.uk)

Supervisor II: Thomas Gessey-Jones (tg400@cam.ac.uk)

Supervisor III: Jiten Dhandha (jvd29@cam.ac.uk)

UTO: Anastasia Fialkov (afialkov@ast.cam.ac.uk)

Project Summary

The hydrogen 21-cm signal is a probe of the typical galaxy population during the first billion years of cosmic history. This signal is complex and depends not only on the ionization history of the Universe but also on many other astrophysical processes, such as the thermal history of the Universe and the distribution of the underlying dark matter. Interpreting observations (including existing upper limits and the upcoming/expected detections) thus requires robust theoretical modelling. However, full end-to-end simulations of the 21-cm signal are very computationally expensive and largely unfeasible due to the complexity of the physics involved and the multi-scale nature of the problem (luminous sources create radiative backgrounds that affect the 21-cm signal over vast cosmological scales). As a result, various approximations and trade-offs have to be used in current models of the 21-cm signal. In this project, we will consider several numerical methods including (1) a semi-numerical approach developed by our group in Cambridge and (2) a fully numerical radiative transfer code C2-Ray. We will compare the outputs of the two methods and verify the precision with which the signals are predicted. This comparison is an essential part of model building and verification and will increase our confidence in the theoretical predictions and thus the insights into the first galaxies and the nature of dark matter precision 21-cm cosmology will bring.

Background

Shortly after the Big Bang, (non-dark) matter was in the form of plasma and, as a result, electromagnetically coupled to photons. As the Universe expanded and cooled, electrons and protons combined to create the first neutral atoms in the history of the Universe, with the simplest and the most abundant structures being hydrogen. This process took place when the Universe was about 400,000 years old. As the matter became neutral, it stopped interacting strongly with electromagnetic radiation leading to the build-up of the Cosmic Microwave Background (CMB).

In latter epochs, as CMB photons pass through neutral hydrogen clouds, an atomic transition of hydrogen (its spin-flip transition) resonates at the wavelength of 21 cm, causing distortions of the otherwise (nearly) perfect CMB black body spectrum at the intrinsic frequency of 1.42 GHz. These distortions, once observed, will allow us to probe the Universe at Cosmic Dawn and the Epoch of Reionization (EoR).

The rate at which absorption or emission of the CMB photons by hydrogen atoms happen depends on the gas density, the background ultraviolet and X-ray radiation produced by stars and black hole binaries, the rate of atomic collisions, velocity flows, and the underlying cosmology. All these ingredients affect the strength of the 21-cm signal and imprint patterns into it (see Figure 1). For example, radiation from the first stars in the Lyman band imprints bubbles in the 21-cm signal on scales of a few tens of comoving megaparsecs. This is owing to the radiation driving spin-flip transitions and coupling the 21-cm signal to (eventually) the gas temperature. Then the first X-ray binaries also affect the 21-cm signal as they emit X-rays photons that heat up the gas. Finally, more massive galaxies forming during the EoR produce a large number of UV photons that re-ionize the gas. As a result of this process, neutral gas gradually disappears and the 21-cm signal vanishes. Hence, through the evolution of the 21-cm signal we can indirectly trace the history of the Universe, and sensitively probe early star and black hole formation, as well as infer the properties of the first galaxies.

The recently launched JWST already provides some insight into the first galaxies. JWST observes massive galaxies at the EoR, which are most likely driving the process of reionization of the intergalactic medium. However, the galaxies which can be directly seen by the JWST are only the brightest ones with the majority of the population remaining below the satellite's detection threshold. The hydrogen 21-cm signal, on the other hand, is a probe of the typical galaxy population, and so would provide complementary information.

Due to the huge scientific potential of a 21-cm signal detection, there are several current and upcoming low-frequency radio experiments such as HERA, LOFAR, NenuFAR and the SKA aiming to directly detect this signal from Cosmic Dawn and the EoR. The correct interpretation of any detection they might make requires robust theoretical predictions of the 21-cm signal, which is where this project comes in.

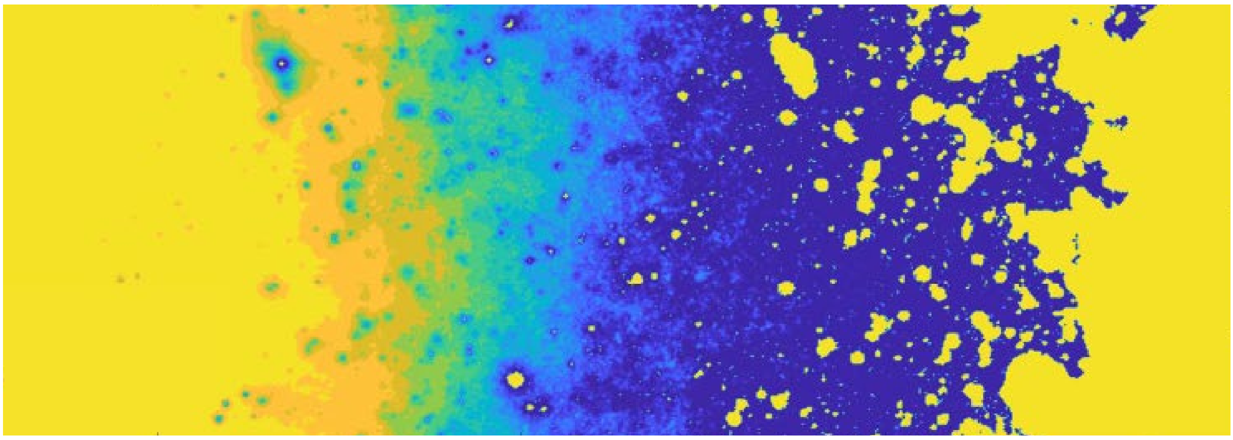


Figure 1.: The evolution of the 21-cm signal over cosmic time, from the cosmic dark ages (left) to the present day (right). The non-uniform structure is the result of the primordial fluctuations in the distribution of matter and the impact of radiation from sources. As the signal evolves it traces key events in cosmic history from cosmic dawn (the first blue bubbles on the left) to reionization (saturation in yellow on the right).

Project Details

In this project, we will contrast the results of two widely used codes in the field of 21-cm cosmology. The first is our in-house 21-cm signal model, hosted privately on GitHub, developed over many years (see, e.g., refs [1-3]). The second is a publicly available radiative transfer code C2-Ray developed by collaborators Ilian and Mellema in Sussex and Stockholm (see refs [4-5]). The codes are fundamentally different in their structure, with the former being semi-numerical in nature while the latter is fully numerical. We will start with the simplest setup possible for both codes (e.g., no sources) and compare the outputs. We will gradually add components and verify whether or not the 21-cm signals produced by the two codes agree. Although both codes are widely used and are cutting-edge, such a detailed comparison has never been made and is an essential step on the way to precision 21-cm cosmology. The insights gained from this comparison will hopefully lead to improvements in both codes and ultimately more accurate scientific conclusions from 21-cm signal measurements.

Skills Required

- Numerical skills, e.g., programming in Python or Matlab.
- Compulsory Part II 'Introduction to Cosmology' or Part III 'Cosmology'
- Useful Part II 'Statistical Physics' and Part II 'Formation of Structure in the Universe'

Useful References (List of important papers/review articles relevant to the project)

- Fialkov et al., Monthly Notices of the Royal Astronomical Society, Volume 432, Issue 4, pp. 2909-2916 (2013)
- Fialkov et al., Nature, Volume 506, Issue 7487, pp.197-199 (2014)
- Cohen et al., Monthly Notices of the Royal Astronomical Society, Volume 472, Issue 2, pp.1915-1931 (2017)
- Mellema et al., New Astronomy, Volume 11, Issue 5, pp.374-395 (2006)
- Ross et al., Monthly Notices of the Royal Astronomical Society, Volume 468, Issue 4, pp.3785-3797 (2017)

General References (List of papers referred to in the project)

- e.g., Furlanetto et al., Physics Reports, Volume 433, Issue 4-6, p. 181-301 (2006)

Project 23: Modelling the impact of cosmology and dark matter on the Dark Ages 21-cm signal

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Project Summary

Cosmologists have a limited understanding of how the Universe evolved between the formation of the Cosmic Microwave Background (CMB) and the formation of the first stars. This period in cosmic history is known as the Dark Ages and a promising probe is the redshifted hydrogen 21-cm signal. The structure of the signal can tell us about the nature of dark matter, the distribution of baryonic matter in the Universe and the cosmological model that best describes the Universe we live in. This signal is yet to be detected, however, there is an increasing interest in the field as many missions are planned to observe the signal from lunar orbit and lunar surface in the next few decades. Accurate and detailed theoretical modelling of the signal is crucial if we are to understand and appropriately interpret the data collected by these Moon based missions (e.g. Figure 1). In this project we will develop a simulation of the dark matter and gas distribution during this period, how they evolve together and calculate the corresponding 21-cm signal (see Figure 2) that arises from self-interactions between molecules in the gas. We will subsequently investigate how changing the cosmological model that goes into our simulations and how varying the properties of dark matter in the model impact the resultant 21-cm signal. The project is timely given the upcoming lunar missions and will give us a deeper insight into the information that these experiments can provide about our Universe.

Figure 1.: Proposals for observations of the dark ages 21-cm signal focus on missions to the Lunar surface or to Lunar orbit. The figure shows one such experiment called the Lunar Surface Electromagnetics Experiment-Night (LuSEE-Night) which is being developed by NASA, University of Colorado Boulder and the USA Department of Energy and is set to launch in late 2025. Correctly interpreting the results from these experiments is crucial if they are to be successful and that requires projects like this one to help us better understand the physics of the early Universe.

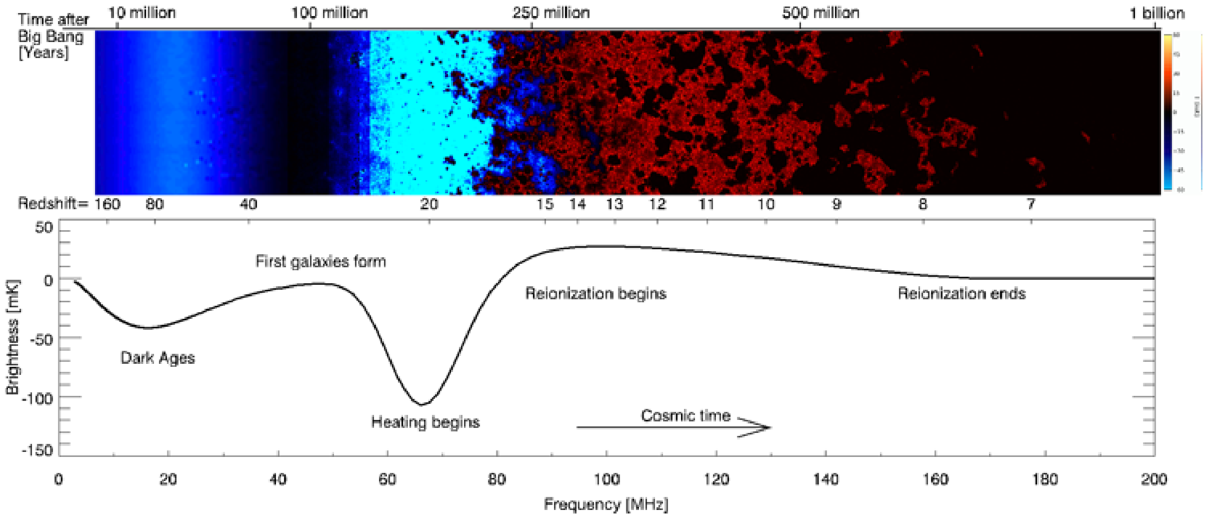

Figure 2.: The top panel shows a representation of the 21-cm signal through time and space and the bottom panel shows the spatially averaged signal. The project focuses on modelling the period between the formation of the CMB on the far left of the figure and the formation of the first galaxies around 100 million years after the Big Bang. The goal is to understand how the timing and depth of the Dark Ages absorption feature is dependent on the cosmological model used and the properties of dark matter.

Background

After recombination, when the primordial plasma of charged particles coalesced into atoms approximately 400,000 years after the Big Bang, the non-dark (or baryonic) matter in the Universe was largely comprised of hydrogen. During this period electromagnetic radiation began to free stream, as the baryonic matter became largely neutral, forming the CMB.

Photons from the CMB passing through clouds of neutral hydrogen drive the rate of an atomic transition in hydrogen known as the spin-flip transition. This creates a distortion in the CMB black body spectrum that if observed will help us to understand the structure of the Universe, the nature of dark matter and the cosmological model that best describes our Universe.

During the Dark Ages, around 400,000 to a few 100 million years after the Big Bang before the first stars formed, the rate of absorption and emission of CMB photons at 21-cm by neutral hydrogen is mediated by collisions within the gas. The collisions couple the spin temperature, a measure of the number of hydrogen atoms in the ground and excited states, to the kinetic temperature of the gas which is cooler than the CMB. This produces an absorption feature in the CMB spectrum. Eventually, due to the expansion of the Universe, the density of the gas reduces as does the rate of collisions and the distortion in the CMB temperature vanishes (e.g. Figure 2). The timing of the signal can therefore tell us about the density of baryons and dark matter, how fast the Universe expanded during this period and potentially the dark matter particle mass.

Observations of the 21-cm signal from this period of cosmic history from Earth are largely impossible due to the Earth's atmosphere and so experimental efforts are focused on placing telescopes on the far side of and in orbit around the Moon. Many missions are planned in the coming decades such as the Cambridge-based CosmoCube and efforts being led in the USA with NASA funding such as LuSEE-Night and FARSIDE (see Figure 1).

Understanding the data from these upcoming missions is crucial and in order to do this we need detailed theoretical models of how the Dark Ages 21-cm signal depends on cosmology and the properties of dark matter. The project can therefore offer a timely insight into a potentially information-rich period in cosmic history.

Project Details

In this project, we will look to simulate the evolution of the dark matter and gas distribution over cosmic time from the formation of the CMB, 400,000 years after the Big Bang, through to the formation of the first stars when the Universe was only a few hundred million years old. Starting with a Lambda-CDM cosmology we will generate initial conditions for the relative velocity between and distributions of dark matter and baryons 400,000 years after the Big Bang. We will then evolve these through to a few hundred million years after the Big Bang tracking the temperature of the gas and the spin temperature of the neutral hydrogen. We will subsequently derive summary statistics on the 21-cm signal from the resultant simulations. We will then invesitgate how these are impacted by changs in the parameters of our cosmological model and to the properties of the dark matter in the model. As such we will learn about how the Dark Ages 21-cm signal can constrain our understanding of the early Universe.

Skills Required

- Numerical skills, e.g., programming in Python or Matlab.
- Relevant Part II Courses: Introduction to Cosmology
- Relevant Part III Courses: Relativistic Astrophysics and Cosmology, Formation of Structure in the Universe, Cosmology

Useful References (List of important papers/review articles relevant to the project)

- e.g., Mondal, Rajesh, and Rennan Barkana. ‘Precision Cosmology with the 21-Cm Signal from the Dark Ages’. arXiv, 15 May 2023. https://doi.org/10.48550/arXiv.2305.08593.

General References (List of papers referred to in the project)

- e.g., Furlanetto et al., Physics Reports, Volume 433, Issue 4-6, p. 181-301 (2006)

Project 24: Extrasolar Trojan Planetesimal Swarms

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Project Summary

The aim of this project is to create a model for the level and spatial distribution of dust created in the destruction of a planet's Trojan planetesimals (i.e., those trapped in its Lagrangian equilibrium points L4 and L5 that orbit the star 60 degrees in front of and behind the planet). This model would be applied to the recent first detection of extrasolar Trojan dust in the PDS70 system.

Background

This project aims to model an as yet unexplored signature of planet-disk interactions, which is dust created between collisions amongst planetesimals trapped in the planet's Trojan swarms. Trojan planetesimals orbit around the Lagrange equilibrium points L4 and L5, resulting in concentrations of planetesimals that orbit 60 degrees in front of and behind the planet. These are a significant feature of the Solar system, with Jupiter's Trojan points particularly populated with asteroids that were captured there soon after the system formed, and have remained throughout the subsequent 4.5Gyr of evolution. Dust is created in collisions amongst these planetesimals creating a collisional cascade extending down to micron-sized dust. Thermal emission from this dust is expected to be relatively bright, but is hard to see due to the ubiquitous dust in the inner Solar System (Kuchner et al. 2000). Nevertheless, dust in Jupiter's Trojans has now been detected and analysed (Liu & Schmidt 2018a; see Fig. 1 right).

The first detection of Trojan dust in an extrasolar planetary system (i.e., dust in a planet's L4 and L5 points) was recently made in the PDS70 system (Balsalobre-Ruza et al. 2023; see Fig. 1 left). This is likely the first of many detections of such dust, motivating a need to understand the dynamics of dust structures formed from Trojan planetesimals. While the dynamics of Trojan planetesimals is relatively well understood within the framework of the restricted three-body problem (Murray & Dermott 1999), the dynamics of dust that may be subject to radiation forces or gas drag has only recently been studied for Jupiter's Trojans (Liu & Schmidt 2018b), but not yet for other planets. Also, while it is well understood how radiation forces affect the collisional cascade for circumstellar dust (Wyatt et al. 2011), and so the brightness of the dust population, this has yet to be considered for Trojan populations.

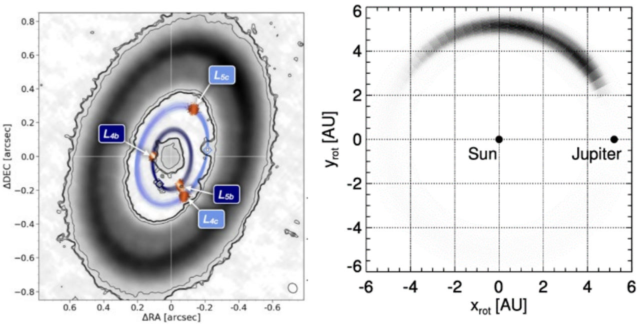

Figure 1.: (Left) Observations of the PDS70 system showing the detection of dust in the L5 point of planet PDS70b (Balsalobre-Ruza et al. 2023). (Right) Simulations of the distribution of dust created in the L5 point of Jupiter in the Solar System (Liu & Schmidt 2018a).

Project Details

This project aims to develop a model for Trojan swarms of planetesimals, their collisional destruction and dust evolution that will be used to predict the brightness of these swarms, and to simulate how they would appear in images. The project will start with N-body simulations to follow the dynamical evolution of the Trojan planetesimals. This will then be post-processed to determine the rate at which collisions occur at different points within the swarm. Simulations will also be run for the evolution of dust created from those planetesimals, by including radiation and gas drag forces, to determine the dust lifetime (e.g., Liu & Schmidt 2018a). This information will then be coupled to analytical considerations (Wyatt et al. 2011) to determine the predicted dust brightness, and used to make simulated images of the dust distribution (e.g., Fig. 1 right). This would be applied to the PDS70 system to assess what the dust detection (Balsalobre-Ruza et al. 2023; Fig. 1 left) implies about Trojan planetesimals in this system, and whether this is a feasible explanation, as well as to consider the observable properties of such Trojan dust more generally.

Skills Required

- The project would involve running N-body simulations using REBOUND (Rein & Liu 2012) and writing programmes to analyse these. This can be in any language; Python should be suitable.
- Attendance at the Part III Planetary System Dynamics course would be beneficial.

Useful References (List of important papers/review articles relevant to the project)

- Balsalobre-Ruza O. et al. 2023, A&A, in press, https://arxiv.org/abs/2307.12811
- Kuchner M. J. et al. 2000, Icarus, 145, 44
- Liu X., Schmidt J. 2018a, A&A, 609, A57
- Liu X., Schmidt J. 2018b, A&A, 614, A97
- Murray C. D., Dermott S. F. 1999, Solar System Dynamics (CUP)
- Rein H., Liu S. F. 2012, A&A, 537, A128
- Wyatt M., Clarke C., Booth M. 2011, CeMDA, 111, 1

Project 25: Are broad debris disks the “scattered disks” of embedded planets?

Supervisor I: Mark Wyatt (wyatt@ast.cam.ac.uk)

Supervisor II: Tim Pearce (timothy.pearce@uni-jena.de)

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Project Summary

The aim of this project is to characterise the structure of planetesimal disks that are shaped by strong scattering encounters with embedded planets. These structures would be compared with those observed around nearby stars, with one application being to the system HD95086 which hosts both a broad (100-300au) debris disk and a planet at its inner edge (58au). The aim is to ascertain whether planetesimals must have formed all the way out to 300au, or whether they reached that distance in interactions, and if so, what additional planets are required to exist in the system.

Background

Around 20% of nearby stars are known to host belts of asteroids and comets, detectable from their collisional grinding that creates dust that can be detected at infrared and millimetre wavelengths. Such belts, known as “debris disks”, are a component of the star’s planetary system, and are shaped by dynamical interactions with those planets (Wyatt 2008). For example, most belts are thought to be truncated at their inner edge by interactions similar to those between Neptune and our Kuiper Belt, while warps, clumps and offsets seen in these disks can be explained as a consequence of dynamical perturbations from planets. The dust in these disks is usually much easier to detect than the planets and these features can be used as a signature of unseen planets (e.g., Hughes et al. 2018).

There is a class of debris disk that is hard to explain within the context of current models: those with broad disks that extend from ~100-300au. Since planetesimals are thought to form in protoplanetary disks on circular orbits, the typical assumption is that these are systems in which planetesimals formed, and were subsequently retained, over a wide range of distances from the star (e.g., Marino et al. 2017). However, it is not clear how planetesimals would be able to form at such large distances due to the long orbital timescales there. The existence of broad disks with narrow gaps also argues that there may be planets embedded within these disks (Marino et al. 2018). As such, models for some broad disks have included planetesimals on orbits that have reached high eccentricities due to scattering interactions with embedded planets (e.g., Geiler et al. 2019). This would mean that the presence of dust and planetesimals at large distance does not require them to have formed that far out. However, such models have assumed these eccentricities and not modelled their origin, and so it is not clear whether this is a viable explanation, and if it is, what the implications are for any embedded planets, which presumably would have to be a new class of relatively low mass planet (to avoid depleting the disk) at ~100au not detectable by other means.

Recent observations from the ARKS Large ALMA programme (to which the project has access) have been made that characterise the structure of several broad disks. These provide a perfect opportunity to test models for their formation. One such system is HD95086, previous observations for which are shown in Fig. 1 (left), which has a 100-300au disk (Su et al. 2017) that extends beyond a planet orbiting at 58au (Desgrange et al. 2022).

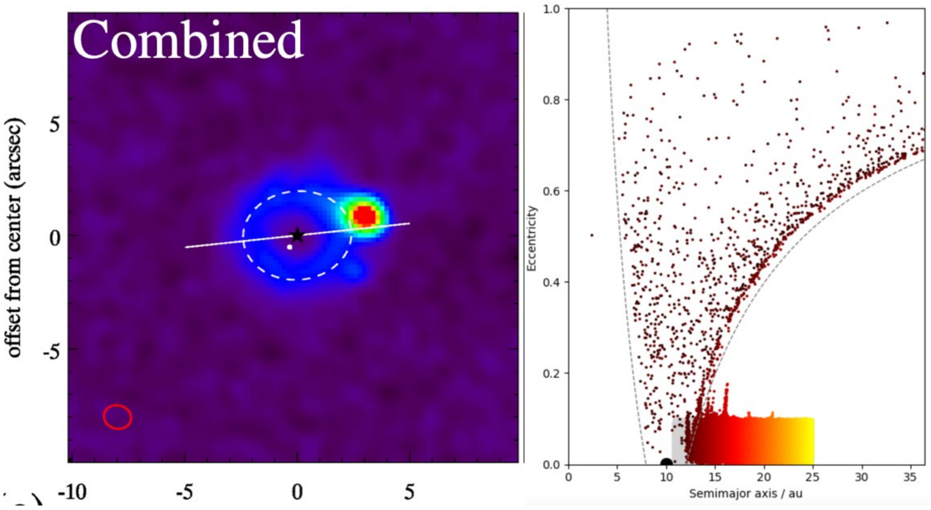

Figure 1: (Left) Observations of the HD95086 system showing in colour scale the detection of a Kuiper belt that extends from 100-300au (Su et al. 2017) [Note that the bright source in red is a background galaxy]. This project would use higher resolution images taken recently as part of the ARKS Large ALMA programme. Also shown is the location of the directly imaged planet HD95086b which sits at the inner edge of the disk.

(Right) N-body simulations of the distribution of planetesimals in an extended planetesimal disk after interacting with a planet at its inner edge. The broad (10-25au) low eccentricity (e<0.1) disk is noticeable, as well as concentrations at specific semimajor axes associated by mean motion resonances with the planet. The dashed lines show the boundary within which planetesimal orbits overlap with the planet and undergo scattering – these form the planet's "scattered disk". This project would analyse such simulations, and create new ones, to explain (newer, higher resolution) observations like those in the left plot.

Project Details

This project aims to develop a model for the structure of broad debris disks with which to assess the possibility that these have an origin in planetesimals formed in a more compact disk, which were subsequently scattered to larger distances by interactions with a nearby and/or embedded planet. The project will be based on N-body simulations to follow the dynamical evolution of planetesimals plus a planet. An initial suite of simulations is available (see Fig. 1 right for a snapshot from one example), in which planetesimals are treated as test particles (i.e., assumed to be massless) which would be analysed to determine the resulting radial profile. This would indicate if a single planet would be able to explain the observations, and if so its properties. This would motivate two sets of further simulations that would be performed to explain HD95086. The first would involve two planets: that known at the disk inner edge, and a second lower mass planet embedded within the disk. The second would consider the effect of the planetesimals having mass. In such a simulation the planet's orbit would migrate, and this could allow a planet to stir a disk to high eccentricity without eventually ejecting all of the planetesimals, since the two could become dynamically decoupled. The project would explore the parameter space of disk mass and planet mass required to explain the observations.

Skills Required

- The project would involve running N-body simulations using REBOUND (Rein & Liu 2012) and writing programmes to analyse these. This can be in any language; Python should be suitable.
- Attendance at the Part III Planetary System Dynamics course would be beneficial.

Useful References (List of important papers/review articles relevant to the project)

- Desgrange C. et al. 2022, A&A, 664, A139
  - Geiler F. et al. 2019, MNRAS, 483, 332
  - Hughes A. M. et al. 2018, ARAA, 56, 541
  - Marino S. et al. 2017, MNRAS, 469, 3518
  - Marino S. et al. 2018, MNRAS, 479, 5423
  - Murray C. D., Dermott S. F. 1999, Solar System Dynamics (CUP)
  - Rein H., Liu S. F. 2012, A&A, 537, A128
  - Su K. Y. L. et al. 2017, AJ, 154, 225
  - Wyatt M. C. 2008, ARAA, 46, 339

Project 26: Bayesian Model Selection of Anisotropic Cosmologies with Type Ia supernova data

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Supervisor II: Will Handley (wh260@cam.ac.uk)

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Project Summary

The standard cosmological model, termed “ΛCDM”, has proven an exceptional, consistent fit for a large and diverse set of observations. However, some tensions exist between ΛCDM and our observations. Most notably, current measurements of the Hubble constant from the local distance ladder are in tension with the early universe inference, assuming standard cosmology. These tensions could be signs of cosmological physics not captured within ΛCDM. Recent studies have claimed detection of local anisotropic signatures in quasar and Type Ia supernova data, violating the assumptions underlying ΛCDM (Secrest et al 2021, Colin et al 2019), while others are in agreement with isotropic cosmology (Dhawan et al. 2023a). In this project, the student will explore various anisotropic cosmologies using a Bayesian model selection framework (e.g., Handley et al. 2015, Handley 2019) applied to the latest compilations of Type Ia supernova data. If the timeline permits, this work will be applied on the Zwicky Transient Facility's second data release of > 3000 Type Ia supernovae with all Northern sky coverage and a well understood selection function.

Background

Modern cosmology relies on the assumptions that the Universe is both the same everywhere (homogeneous) and the same in all directions (isotropic). In General Relativity this amounts to adopting the Friedmann-Lemaitre-Robertson-Walker (FLRW) description of space-time, forming the basis of ΛCDM and therefore almost all cosmological data analysis today.

Recent studies have claimed detection of a non-zero dipole anisotropy in large sets of Type Ia supernovae (SNe Ia) data (e.g., Colin et al 2019).

Ongoing surveys like the Zwicky Transient Facility have increased the discovery rate of SNe Ia manifold (e.g., Dhawan et al. 2022a) and minimised systematics due to a uniform observing strategy. Forthcoming surveys like the Rubin Observatory and the Roman Space Telescope will increase the amount of SN Ia data by an order of magnitude. This will greatly improve the constraining power of our data and allow us to make stronger determinations about our local Universe. Hence, it is timely to study these potentially important low-redshift anisotropies.

Project Details

In this project, the student will compute the Bayesian evidence for higher order multipoles, like the quadrupole, as described in Cowell et al. 2023 as well as anisotropies in dark energy models described in Dhawan et al. 2020 which range a series of physical motivations including late time transitions, dynamical dark energy and modified gravity. The project requires knowledge of Bayesian statistics and nested sampling techniques. Methods like MultiNest and nestle have been used in context of SN Ia data analysis. This project will therefore require the student to:

- Perform a literature review of well-motivated anisotropy models and datasets used to constrain them.
- Write code to utilise cutting edge softwares like PolyChord for Bayesian evidence calculation.
- Analyse the model parameter constraints under different groupings of SN Ia systematics.
- Infer Bayes Factor values for the models.
- If time allows, apply the method to future survey predictions from the Rubin Observatory and Roman Space Telescope.
- For the computation with current data, the project will start with the Pantheon+ dataset and during the course of the project, ZTF's second data release is expected to be available which will increase the low-redshift statistics by a factor of ~ 4 – 6.

Skills Required

- Required: an interest and motivation to learn basic Python programming and analysis of real cosmological data, basic cosmology knowledge.
- Desired (though not essential):
    - Experience coding with Python and analysing large datasets. Support will be provided in the case of limited programming experience.
    - The project would benefit from the student having taken Part II cosmology.

Useful References (List of important papers/review articles relevant to the project)

- Handley et al. 2015, MNRAS, 453, 4384
- Dhawan et al. 2017, JCAP, 10, 4
- Dhawan et al. 2020, ApJ, 894, 54
- Dhawan et al. 2023, MNRAS, 519, 4841
- Brout et al. 2022, arXiv:2202.04077

General References (List of papers referred to in the project)

- Secrest et al (2021) "A Test of the Cosmological Principle with Quasars" https://arxiv.org/abs/2009.14826
- Colin et al (2019) "Evidence for anisotropy of cosmic acceleration" https://arxiv.org/abs/1808.04597
- Planck Collaboration (2020), "overview and cosmological legacy" https://arxiv.org/abs/1807.06205

Project 27: Unravelling Dark Matter: Exploring FDM and MDM Models

Supervisor I: Anastasia Fialkov (afialkov@ast.cam.ac.uk)

Supervisor II: Tibor Dome (td448@cam.ac.uk)

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Project Summary

The nature of dark matter remains elusive. This project focuses on two intriguing candidates - fuzzy dark matter (FDM) and mixed dark matter (MDM), which consists of a combination of cold dark matter (CDM) and FDM. FDM, composed of extremely light bosons, exhibits unique solitonic cores in halos, leading to novel dynamics not observed in CDM. However, simulating FDM and MDM presents challenges due to their distinct behaviours, making it necessary to develop advanced computational techniques.

Through a combination of in-house simulations and post-processing approaches, the project will compare FDM and MDM models to simple CDM simulations, using well-established galaxy formation models to predict the evolution of structures. Key properties such as star formation histories and metal enrichment will be studied, and stellar population synthesis codes will be utilized to generate galaxy spectra and magnitudes, enabling the assessment of star formation onset and stellar population ages. By comparing the simulated spectra with observational data from the James Webb Space Telescope (JWST), the project will contribute to ruling out extreme FDM models.

Furthermore, if time permits, halo merger trees and empirical models will be used to model galaxy formation in MDM, leading to a better understanding of the nature of dark matter and aiding the interpretation of experimental results. Overall, this investigation will contribute valuable insights into the large-scale structure of the Universe and the properties of dark matter, furthering our comprehension of fundamental cosmological phenomena.

Background

In the study of the large-scale structure of the Universe, cosmological models that include cold dark matter (CDM) have been successful in explaining various phenomena such as the Cosmic Microwave Background, galaxy clustering, and weak gravitational lensing. However, CDM faces challenges when it comes to modeling structures on smaller scales, around 10 kiloparsecs or less.

Two notable problems are the "core-cusp" discrepancy between galaxy density profiles in CDM models and observations, and the unexpected absence of classical bulges in about 80% of observed galaxies. These issues are often attributed to the complexity of modeling baryonic physics, including star formation, supernovae, and black-hole feedback (Del Popolo & Le Delliou 2017).

An alternative approach to address these problems involves considering different types of dark matter (DM). One intriguing model is fuzzy dark matter (FDM, Hui et al. 2017), which proposes that DM is composed of extremely light bosons with a de Broglie wavelength of about 1 kiloparsec. FDM introduces solitonic cores in the centres of halos, and in models with axion self-interactions, these cores can undergo a phase transition from dilute to dense configurations.

Unlike CDM, FDM behaves like nonrelativistic scalar matter described by a wave function ψ that sources and interacts with the Newtonian gravitational potential. This leads to a coupled Schrödinger-Poisson equation governing FDM dynamics. Extracting FDM behaviour from simulations requires high spatial resolution to resolve the de Broglie wavelength not only in small high-density regions but also in extensive low-density regions if high-speed flows are present. Consequently, simulating FDM in full cosmological simulations is more challenging compared to CDM simulations, which can be efficiently evolved using N-body algorithms.

The unique features of FDM open up the possibility of comparing it with CDM and mixed dark matter (MDM), a combination of CDM and FDM. Observational constraints from the (non-)observation of star-forming filaments or a delayed onset of star formation at Cosmic Dawn can be used to test FDM-like models (e.g., following Esmerian and Gnedin 2021). Utilizing early release data from the James Webb Space Telescope (JWST), researchers have already started probing FDM-like scenarios (Gong et al 2023).

To bridge the gap with observations, scientists ideally aim to conduct full hydrodynamical simulations of different DM models, including baryonic feedback on galactic scales. Alternatively, they can post-process dark-matter-only (DMO) simulations and adopt empirical or semi-analytical models to represent galaxy and star formation processes. While the former approach is more precise, the latter is less computationally expensive and allows for exploring a wider range of galaxy formation physics.

Simulating FDM and MDM accurately is demanding. In large volumes that do not resolve the de Broglie wavelength, N-body simulations with FDM initial conditions can reproduce the suppression of small-scale clustering. Some modified hydro solvers, incorporating a "quantum pressure" term inspired by the Madelung transformation of the Schrödinger equation, account for coherence effects around the de Broglie wavelength. However, these methods encounter issues with zero-density regions where quantum pressure diverges. Hence, only direct solutions of the Schrödinger equation can fully capture the nonlinear wavelike dynamics in collapsed FDM structures. For reliable MDM simulations, researchers use two coupled gravity solvers: a standard N-body solver for the collisionless component and a spectral gravity solver for the Schrödinger-Poisson equation governing the FDM component.

Project Details

In this project, we will analyse our in-house FDM simulations (that were run down to redshift z ~5 at which methods break) and DMO MDM simulations (partially still running and will be stopped at z=0) The hydrodynamical simulations employ the well-established Illustris-TNG galaxy formation module, predicting the formation and evolution of galaxies. We will compare the simulation outputs to simple CDM simulations, focusing on galaxy properties like star formation histories and metal enrichment. State-of-the-art stellar population synthesis codes like FSPS will help us generate galaxy spectra and magnitudes, offering insights into star formation onset and average stellar population ages. By comparing mock spectra with JWST data in collaboration with observational galaxy experts in the Kavli, we can assess extreme FDM models, because these models have more pristine signatures at higher redshift where large scale structure evolution is more linear and there is less degeneracy with baryonic physics. If time allows, we will use Rockstar and Consistent Trees to post-process DMO MDM simulations and obtain halo merger trees. Once constructed, empirical models or SAMs will be applied to model galaxy formation in MDM, calibrating them based on observations. These comparisons (CDM to FDM/MDM and simulations to observations) will improve our understanding of the nature of DM and aid in interpreting results from telescopes such as JWST.

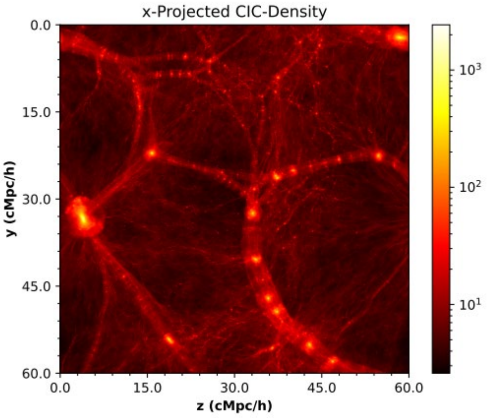

Figure 1.: The distribution of CDM in an MDM simulation at z=20. The non-uniform structure is the result of primordial fluctuations in the distribution of matter that grow to form linear and non-linear structures on Mpc scales. Cosmic nodes and the filamentary highways of the cosmic web can be well discerned.

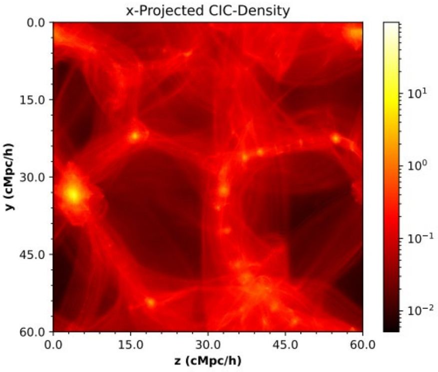

Figure 2.: The FDM counterpart to Fig. 1 of the same MDM simulation at the same redshift of z=20. Interference patterns are visible around cosmic filaments and solitonic cores in high-density nodes.

Skills Required

- Numerical skills, e.g., programming in Python, basic knowledge of cosmology and dark matter.
- Courses:
  - Compulsory Part II 'Introduction to Cosmology' or Part III 'Cosmology' ;
  - Useful Part II *'Statistical Physics'* and Part II *'Formation of Structure in the Universe'*

Useful References (List of important papers/review articles relevant to the project)

- e.g., Del Popolo & Le Delliou, MDPI Open Access, Volume 5, Issue 17, 2017
- Hui et al., PRD, Volume 95, Issue 4, 2017

- Mocz et al., PRL, Volume 123, Issue 14, 2019

General References (List of papers referred to in the project)

- Esmerian and Gnedin, ApJ, Volume 910, Issue 2, 2021
- Gong et al., ApJ, Volume 947, Issue 1, 2023

Project 28: Deciphering stellar halos of nearby massive galaxies

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Project Summary

The goal of the project is to investigate the accretion history of late-type (spiral) galaxies through the study of the radial surface brightness profiles of their halos. This can be achieved in several steps :1) measuring the radial stellar halo profiles of nearby massive late type galaxies; 2) quantifying the significance of the breaks in the radial surface brightness profiles; 3) carrying out similar analyses for simulated galaxies; 4) searching for correlations between breaks in the halo profiles and i) tidal features around the galaxies, ii) the environment in which galaxies are located (field/group vs galaxy cluster).

Background

The high-surface brightness and easily visible central regions of galaxies are surrounded by low-surface brightness, diffuse and ghostly stellar halos, made up from tidally stripped stars from merging smaller objects. Although stellar halos do not contain any significant amount of mass they hold the record of the past accretion events experienced by the galaxy they enshroud. This is because i) the accreted stellar halos are dominated by the material from a small number of most massive dwarfs and ii) orbital times, and hence mixing times, are very long in the halo. In principle, every stellar halo has a unique appearance, but their formation paths can be deciphered if stellar halos are categorised with a small number of robust statistics. Several such statistics have been used successfully in the studies of the Milky Way stellar halo (see e.g., Deason et al 2013). These include the radial density slope, the flattening of iso-density contours and the position and strength of the radial density break. The break is the abrupt change in the steepness of the stellar halo radial density profile and can be measured by fitting power-law models to the surface brightness measurements (see Sánchez-Alarcón et al 2023 for an attempt to carry out a break analysis on external galaxies).

Deason et al (2013) show that strength of the break and its location can be intercepted to reconstruct the accretion history of the galaxy (see Fig. 1 for examples of the breaks in some halo profiles). They show that a stellar halo with a prominent break is usually dominated by a single massive accretion event, such as in the case of our own Galaxy. The location of the break corresponds to the last apo-centre of the massive dwarf galaxy, the main progenitor of the stellar halo. In the Milky Way's neighbour, the M31, the stellar halo shows no obvious break - this is the result of continuous accretion of satellites, depositing their tidal debris over a wide range of apo-centres. In this case, multiple breaks combine to form a roughly continuous radial profile.

In some cases, the stellar halo can be seen to separate into individual tidal features such as streams and shells. Their properties are a function of the type of merger that happened (see e.g., Hendel & Johnston 2015), hence they are also probes of the late galaxy mass assembly. For instance, tidal tails are large, elongated structures generated during the merger of two massive galaxies (e.g., Toomre &

Toomre 1972, Barnes 1992, Hopkins et al 2008); streams originate from the disruption of a lower-mass companion (e.g., Bullock & Johnston 2005, Belokurov et al 2006, Johnston et al 2008); while shells are likely formed during intermediate-mass radial mergers (e.g., Quinn 1984, Prieur 1990).

Stellar halos do not only contain accreted material, but their central regions are also predicted to hold a sizeable proportion of the stars formed in-situ (see e.g., Cooper et al 2015). The in-situ components typically do not extend very far and often produce a radial density break well within the scale-length of the galaxy's disc (for late types). To date, in-situ stellar halos have remained largely unstudied but are hypothesised to contain the record from some of the earliest phases of the galaxy formation (see e.g., Belokurov & Kravtsov 2021).

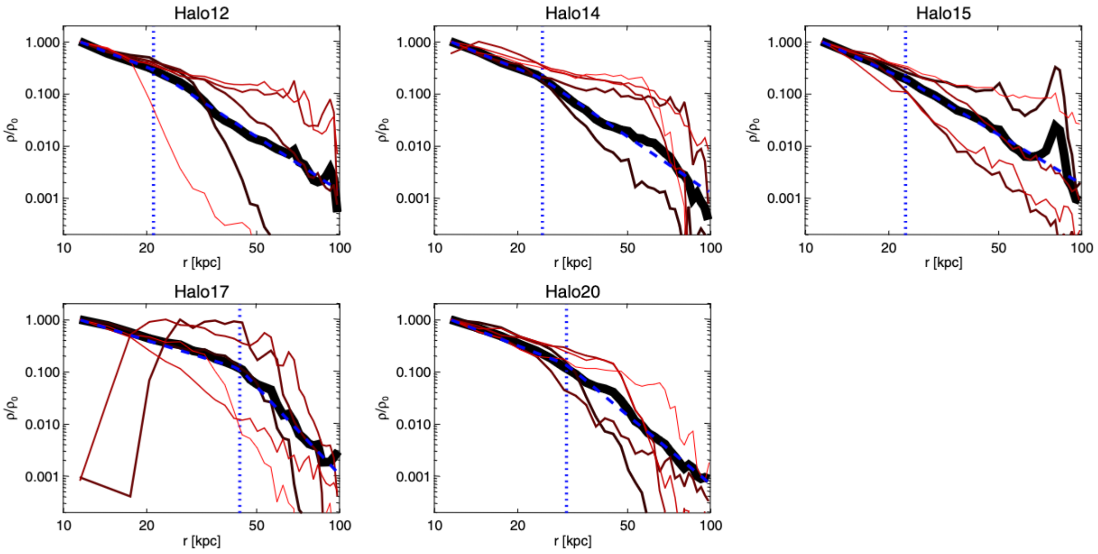


Figure 1. Radial density profiles of the 11 BJ05 stellar halos. The thick black line shows the overall profile for the 15 most massive satellites that contribute to the stellar halo within 100 kpc. The thinner lines show the profiles for the five most massive accreted subhalos. The fraction (by mass) contributed to the stellar halo decreases from thicker black to thinner red lines. The blue dashed line shows the best-fit BPL profile for the stellar halo, and the vertical dotted line indicates the corresponding break radius.

Figure 1.:Adapted from Figure 1 of Deason et al 2013.

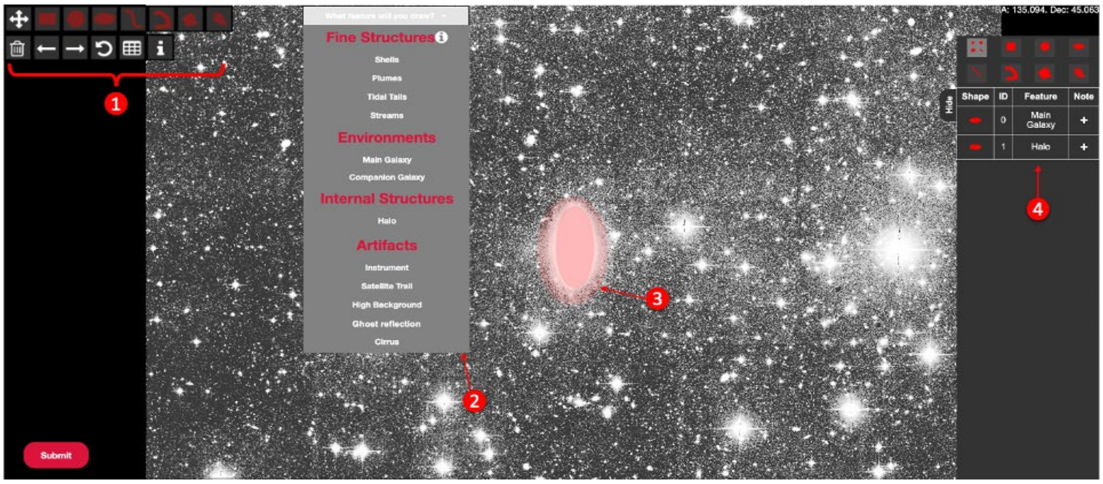
Project Details

The project will use the large low surface brightness (LSB) dataset published by Sola et al 2022. It contains the coordinates of the contours and labels (i.e., type) of around 10,000 manually annotated LSB features, using a dedicated annotation tool (see Fig. 2 for the interface of the annotation tool). The dataset includes stellar structures (halos, tidal tails, streams, shells) but also sources of contamination that make the identification of tidal features more complicated (galactic cirrus, artefacts from the instrument). Information about the geometry, surface brightness and photometry of these features were also computed.

The goal of the project is to investigate accretion histories of late-type galaxies through the study of their radial halo profiles, relating the presence or absence of a break to the past accretion events. To that end, the first step is to measure the halo radial surface brightness and/or density profiles of a complete, volume-limited sample of nearby massive late type galaxies. The second step consists in quantifying the significance of the potential breaks, to distinguish between several accretion histories.

These measurements will be compared to the predictions of numerical simulations of galaxy formation (e.g., Pillepich et al 2014, Rodriguez-Gomez et al 2016). We can use publicly available simulations such as Illustris TNG (see https://www.tng-project.org/data/). Radial density profiles of such mock stellar halos will be built and modelled in exactly the same way as the observed ones.

Finally, it will be interesting to determine whether the breaks in halos radial profiles can be related to the presence of tidal features which are generated during recent mergers, to determine whether these recent mergers may be responsible for the shapes of the halos' profiles. The database of LSB features by Sola et al 2022 will be used to investigate potential correlations (see Fig 3, where Sánchez-Alarcón et al 2023 investigate the link between the type of the break and the presence of interaction signs like tidal features). As the galaxies probed are located in various environments (field, group, cluster) it will also be possible to investigate potential correlations between the breaks in radial profiles and the environment (e.g., Pranger et al. 2017; Watkins et al.2019)).



Shape	ID	Feature	Note
⬬	0	Main Galaxy	+
⬬	1	Halo	+

Figure 2.: Illustration of the interface of the annotation server (Sola et al 2022). Drawing mode: 1: Drawing shapes; 2: Label selection; 3: Annotation already drawn; 4: Summary table

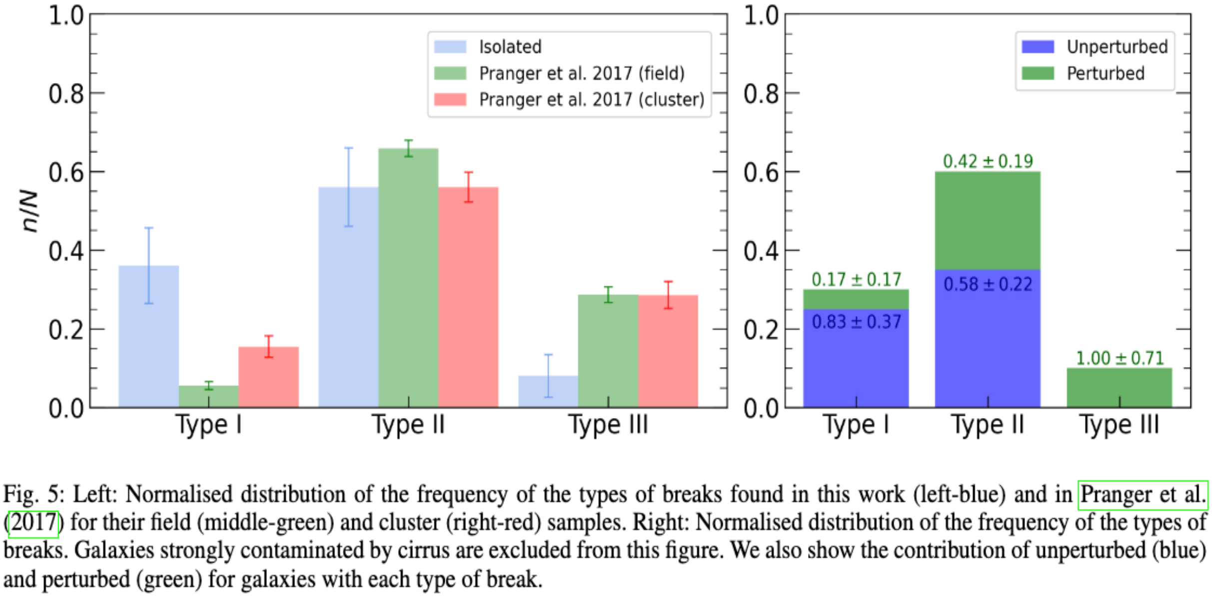


Fig. 5: Left: Normalised distribution of the frequency of the types of breaks found in this work (left-blue) and in Pranger et al. (2017) for their field (middle-green) and cluster (right-red) samples. Right: Normalised distribution of the frequency of the types of breaks. Galaxies strongly contaminated by cirrus are excluded from this figure. We also show the contribution of unperturbed (blue) and perturbed (green) for galaxies with each type of break.

Figure 3.:Figure 5 from Sanchez-Alarcon et al 2023

Skills Required

- Coding (Python).
- Lecture courses: Part II - Stellar Dynamics and Structure of Galaxies. Part III - The Life and Death of Galaxies.

Useful References (List of important papers/review articles relevant to the project)

- Belokurov & Kravtsov 2021
- https://ui.adsabs.harvard.edu/abs/2022MNRAS.514..689B/abstract
- Bullock & Johnston 2005 https://ui.adsabs.harvard.edu/abs/2005ApJ...635..931B/abstract
- Cooper et al 2015 https://ui.adsabs.harvard.edu/abs/2015MNRAS.454.3185C/abstract
- Deason et al 2013 https://ui.adsabs.harvard.edu/abs/2013ApJ...763..113D/abstract
- Hendel & Johnston 2015 https://ui.adsabs.harvard.edu/abs/2015MNRAS.454.2472H/abstract
- Pillepich et al 2014 https://ui.adsabs.harvard.edu/abs/2014MNRAS.444..237P/abstract
- Rodriguez-Gomez et al 2016
- https://ui.adsabs.harvard.edu/abs/2016MNRAS.458.2371R/abstract
- Sola et al 2022 https://ui.adsabs.harvard.edu/abs/2022A%26A...662A.124S/abstract
- Sánchez-Alarcón et al 2023 https://ui.adsabs.harvard.edu/abs/2023arXiv230702527S/abstract

Project 29: Detecting strongly lensed core-collapse supernovae with the Vera C. Rubin Observatory

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Project Summary

Strong gravitationally lensed supernovae (gLSNe) are an excellent cosmological probe, expected to precisely measure the present-day expansion rate (the Hubble constant) and dark energy properties. In recent years, with the advent of wide-field time-domain surveys, the study of gLSNe has progressed from a theoretical possibility to detailed studies of a handful of objects. However, to use gLSNe for precision cosmology, we require large samples which will only be possible with near-future surveys. This project will build on several works in the literature studying the detection rate of lensed Type Ia supernovae, where it was shown that the observing strategy used by the survey under consideration plays a crucial role in the discovery potential. In this project the student will investigate the discovery rate of lensed core-collapse SNe by the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST), using the current baseline LSST survey observing strategy. The project will involve computing the observed magnitudes, colours, and lensing parameters such as time-delays and magnifications. Based on the inferred parameters, the student will also determine how well can the lensed CC SNe be distinguished from unlensed SNe, or "background" sources of contaminants.

Background

The discrepancy between the local measurement of the Hubble Constant (H0) from the Cepheid-calibrated supernova distance scale and the inference of H0 from the cosmic microwave background (CMB) assuming the standard cosmology is a highly debated topic in the field. With the tension at a 5σ level, it is imperative to answer whether this is a sign of new cosmological physics or unknown systematics. Strongly lensed supernovae (gLSNe) are a powerful new cosmological probe, which is completely independent of the local distance ladder calibration with only a weak dependence on the cosmological model. Therefore, this new probe has the strong potential for illuminating the cause of the tension since it is not sensitive to the same systematics as either the local distance scale or the CMB. With time-domain surveys like LSST expected to be online soon, we would be routinely able to discover these sources. Measuring H0 from strongly lensed SNe requires a model of the gravitational potential of the deflector galaxy and an estimate of the time-delay between the multiple images. Recent studies (e.g., Arendse et al. in prep, Huber et al. 2019) have investigated the impact of a realistic survey strategy on the discovery rate of gLSNe and the properties of the expected cosmologically useful sample, and find that the subsample with sufficiently-long time-delays would yield a H0 measurement at the 1.5% precision.

However, previous studies have focussed on lensed Type Ia supernovae. Type Ia supernovae – which are thermonuclear explosions of a white dwarf in a binary system – have been excellent distance indicators for cosmology, when used as standardisable candles. However, core collapse supernovae

(CCSNe) can also be used robustly for cosmology from time-delay distances. Since they are the most abundant subtype of supernovae, they are expected to comprise a large fraction of the gLSNe discovered by LSST. The aim of this project is to simulate the detectability of the lensed CCSN sample in the LSST data stream. Since the CCSNe have a larger spread in their observed luminosity, it will be crucial to determine the observables that can distinguish lensed CCSNe from their unlensed counterparts.

Key expected results from this project would be:

1. Selection criteria to distinguish lensed SNe of all types from other "background transients" or contaminants.
2. An estimate of the precision in cosmological inference, specifically H0 from lensed CC SNe.

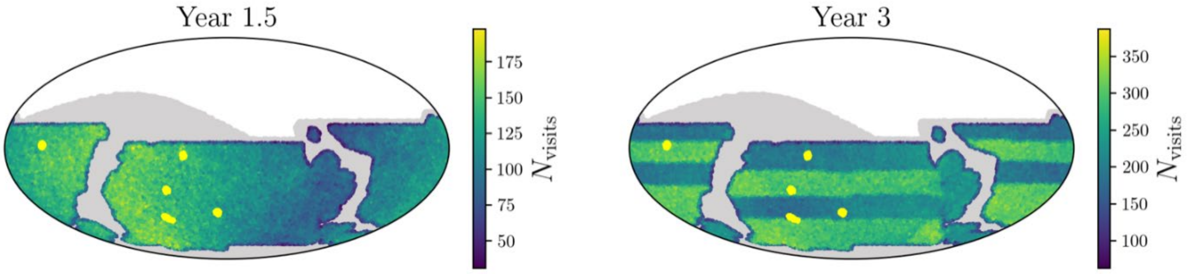

Figure 1.: LSST cadence for the first three years of survey operations. The grey area is the complete footprint, and the coloured area is the wide-fast-deep survey (WFD ~ 18,000 square degrees). For the first 1.5 years the cadence is uniform after which rolling cadence begins. The aim of the project is to generate the image time series for lensed CCSNe with this cadence and compute the inferred properties for the sample.

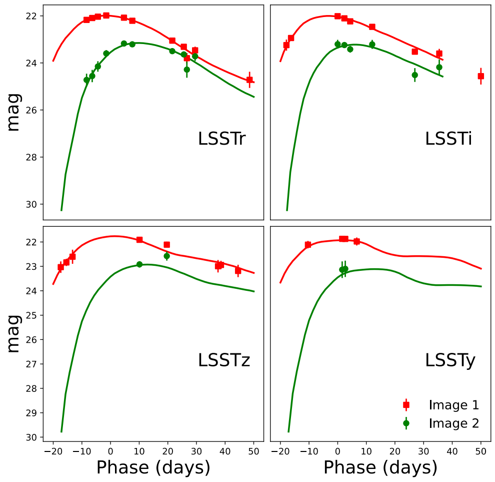

Figure 2.: Example lightcurve simulations with the model fit for the time-delay inference from the lensed SNIa population expected with the realistic cadence simulation, in Figure 1 (Arendse et al. in prep.).

Project Details

For the project, the student will use publicly available packages like lenstronomy, sncosmo and implement the LSST cadence with a core-collapse SN template. Products from the Arendse et al. work currently in preparation will be available for the student, since the paper is expected to be submitted by the beginning of the project. However, independent of the publication timeline, the student will have access to relevant products via the github repository.

The action items for this project will involve:

- Familiarising with cadence summary files
- Simulate images with lenstronomy
- Injecting the lensed SN images with CC SNe
- Computing the output parameters in the LSST filters for CC SNe
- Comparing different templates (e.g., Nugent et al., Vincenzi et al.) and different subtypes, e.g Ib/c, IIP, IIn etc.

Skills Required

- Required: an interest and motivation to learn basic Python programming and analysis of real cosmological data, basic cosmology knowledge
- Desired (though not essential):
    - Experience coding with Python and analysing large time-series datasets. Support will be provided in the case of limited programming experience.
    - While no specific Part II or Part III course is required for this project, the student would benefit from having taken structure and evolution of stars, and cosmology.

Useful References (List of important papers/review articles relevant to the project)

- Goldstein et al. 2019, ApJS, 243, 6
- Huber et al. 2019, A&A, 631, 161
- Goobar et al. 2023, Nat. As., 129
- Kelly et al. 2023, Science, 380, 1322
- Bayer et al. 2021, A&A

General References (List of papers referred to in the project)

- Modjaz et al. 2019, Nat. As., 3, 717
- Birrer et al. 2021, JOSS, 6, 3283
- Suyu et al. 2023, arxiv:230107729

Project 30: Constraints on the evolution of protoplanetary discs from their initial conditions

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Supervisor III: Álvaro Ribas (ar2193@ast.cam.ac.uk)

UTO: Cathie Clarke (cclarke@ast.cam.ac.uk)

Project Summary

This project involves forward modelling the correlation between the mass accretion rate and carbon monoxide (CO) flux of the 3 Myr old protoplanetary discs in the Lupus star-formation region (SFR) to determine their initial properties. This exercise will be based on an available public code that allows to compute the CO flux (as a function of the CO disc temperature) and the mass accretion rate for a distribution of initial conditions in the viscous and magnetohydrodynamic (MHD) wind scenario (see Background). The aim of this project is to compare the recovered initial properties with measurements of the disc fluxes and sizes in very young (<0.1 Myr) discs. This will allow us to determine which evolutionary scenario best reproduces the observations.

Background

Protoplanetary discs are the cradle of planets. Understanding how they evolve informs us about the availability of dust and gas for planet formation. This project will use observational data derived from star-disc systems with different ages to understand the nature of the processes driving disc evolution. In particular, the aim is to determine the dominant process driving radial inflow of gas (accretion) onto the star: these are the viscous model (in which angular momentum is *redistributed* in the disc so as to allow accretion onto the star) or the MHD-wind scenario, (in which angular momentum is *removed* by powerful magnetothermal winds). The approach will be to explore, in each of these scenarios, what is the distribution of initial disc properties that can explain the distribution of accretion rates and flux of emission from carbon monoxide (CO) measured in discs in the 3 Myr old Lupus star forming region (see Figure 1). These required initial conditions include constraints on the initial sizes of discs which can be directly compared with those observed in the much younger systems observed in the VANDAM sample (e.g., the initial disc size distribution in Figure 2).

Project Details

The starting point of the project will be to determine the parameters (slope, intercept and scatter) of the correlation between mass accretion rate and CO flux in Lupus discs (data from Manara+22). The student will then use a publicly available protoplanetary disc population synthesis code (https://github.com/fzagaria/COpops) to forward model this correlation. The first step will be to determine a disc-averaged temperature profile from the correlation between CO fluxes and sizes (see Figure 3). This profile will then be used to run some exploratory models to understand how the predicted evolution in the accretion rate - CO flux plane depends on the initial conditions in each of the two scenarios ("viscous" and "MHD wind"). Then, the student will generate families of models and compare the slope and scatter of the simulated populations with the correlation between CO fluxes and mass accretion rates in Lupus (see Figure 1). The viscous and MHD-wind models are expected to provide very different initial conditions (e.g., we expect the required initial sizes in the MHD-wind case to be larger because such models do not exhibit the radial expansion seen in viscous models). Comparing these models with independent measurements of fluxes and sizes in young star forming regions, will allow us to determine what model best explains disc evolution.

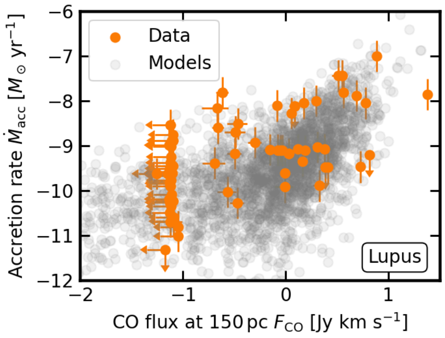

Figure 1.: Correlation between the mass accretion rate and CO flux in Lupus. A population of models is shown in grey for the viscous case.

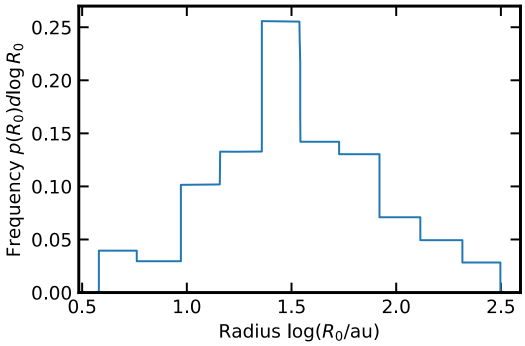

Figure 2.: Distribution of initial disc sizes from the VANDAM survey (adapted from Sheehan et al. (2022)

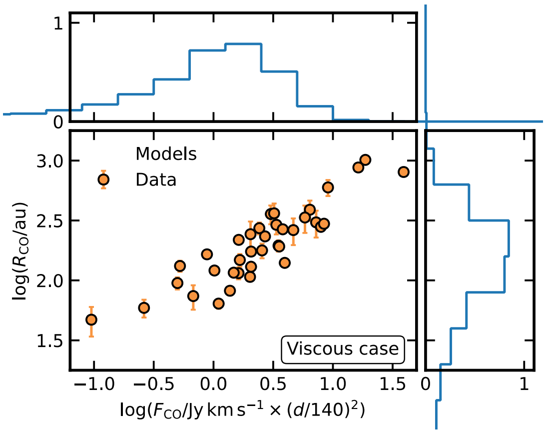

Figure 3.: Correlation between CO flux and CO emission size

Skills Required

- The project will require programming in Python.
- A background in fluid dynamics, for example the Part II course “Astrophysical Fluid Dynamics”, is desirable.

Useful References (List of important papers/review articles relevant to the project)

- Manara et al., (2022): PPVII review on disc evolution (see https://arxiv.org/pdf/2203.09930.pdf); Lodato et al., (2017): for viscous models (see https://arxiv.org/pdf/1708.09467.pdf); Zagaria et al., (2023): see https://arxiv.org/pdf/2304.01760.pdf; Tabone et al., (2022a,b) for MHD wind models (see https://arxiv.org/pdf/2111.10145.pdf, https://arxiv.org/pdf/2111.14473.pdf).

General References (List of papers referred to in the project)

- Worth having a look at Andrews (2020) for a general review on protoplanetary discs (see https://arxiv.org/pdf/2001.05007.pdf).

Project 31: New constraints on the Cold Dark Matter substructure spectrum with the Galactic mille-feuille

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Project Summary

This Project proposes to test the pioneering new method to probe the Dark Matter (DM) substructure at the mass scale inaccessible to any other observational technique, i.e., below 10^6 Solar mass. This technique relies on the fact that the bulk of the Galactic stellar halo has been deposited into the Milky Way as part of the single ancient accretion event, the so-called Gaia Sausage/Enceladus merger (GS/E). The GS/E stars share similar initial conditions at the time of the progenitor galaxy disruption and phase-mix as a whole to produce a series of thin 2-D sheets in phase-space - the Galactic mille-feuille. The stellar sheets enclose a large volume from 3 to 30 kpc from the Galaxy's centre. As a result, all DM sub-halos whose orbits enter the inner Milky Way have to interact with the mille-feuille, perturbing its sheets and yielding an observable signal.

The main aim of the Project is to gauge the minimal DM sub-halo mass which can be detected either by estimating the amplitude of perturbation analytically or by running a set of N-body simulations similar to those presented in Davies et al (2023). Read the Project Details about the possible Project extensions.

Background

One strong and testable prediction of modern Cosmology posits that in the early Universe, Dark Matter (DM) starts collapsing first and ends up arranging itself into a hierarchy of dense clumps of all sizes (e.g., White & Rees 1978). For example, by redshift z = 0, a DM halo with a Milky Way mass is predicted to contain hundreds of thousands of subhalos (e.g., Diemand et al. 2008; Springel et al. 2008), some as massive as 10^9 $M_\odot$, but the lower mass subhaloes are too feeble to kick-start star-formation, and, hence, completely devoid of light. Nonetheless, detecting these dark halos through their gravitational effects may be feasible with existing technology and quantifying their abundance will shed light on the nature of Dark Matter.

So far, two promising experimental setups have been put forward, both to do with the minuscule perturbations the dark substructure inflicts on test particle orbits in the gravitational potential in question. In one case, the role of such test particles is played by photons travelling in the density field of a massive galaxy acting as a gravitational lens. Intervening dark substructure then would either cause flux anomalies in the lensed images if the source is a quasar (e.g., Dalal & Kochanek 2002) or send ripples through the lensed arcs if the source is extended (e.g., Vegetti et al. 2010). Alternatively, Galactic stellar streams can be used as bundles of test particles to probe the lumpiness of DM distribution. During close flybys, the invisible subhalos ought to ruffle the orbits of stars in the stream, imprinting characteristic small-scale features in the stream's density (see e.g., Erkal & Belokurov 2015a,b).

This Project is concerned with a new DM substructure detection technique, in essence, similar to the stellar stream perturbation method, but with a much larger cross-section to interactions with DM subhalos and thus predicted to have a higher sensitivity in the low-mass range. Stellar streams are great for low-mass sub-halo detection because they are fragile, in fact there is no self-gravity in the stream at all, the structure only appears coherent due to the similarity of the initial conditions of its constituent stars. However, streams are inherently 1-D objects and thus have low cross-section for interaction with DM sub-halos. Just like stellar streams, Galactic mille-feuille is formed via the same process of phase-mixing but is composed of a sequence of 2-D sheets (in fact, all sheets are connected into one giant and stretched and folded spiral) and therefore is capable of interacting multiple times with every sub-halo orbiting at similar distances from the MW centre. Therefore, the mille-feuille can be thought of as a large array of sheets, able to capture the entire population of inner subhaloes over a long timescale.

The data from the Gaia satellite has recently been used to confirm the hypothesis of Deason et al (2013) that the MW's stellar halo is dominated by the tidal debris from a single ancient merger event (GS/E, see Belokurov et al 2018; Helmi et al 2018). The GS/E progenitor dwarf galaxy arrived at the MW some 8-11 Gyr ago, spiralled in, losing orbital angular momentum and energy. Its orbit quickly radialised (see Vasiliev et al 2022) and the dwarf galaxy fell apart filling the inner MW with its tidal debris. Once packs of stripped stars are deposited into the host's gravitational potential, in principle, their distribution in the space of integrals of motion (e.g. energy & angular momentum) barely changes, but their phase-space density constantly evolves. Small differences in stars' orbital frequencies eventually translate into orbital phase offsets that accumulate with time in the process known as phase-mixing. As the stellar debris cloud spreads over the Milky Way, the increase of its spatial extent is balanced by the thinning out of the velocity distribution, keeping the phase- space density constant in accordance with Liouville's theorem (see Helmi & White 1999). As the debris cloud continues to stretch in the phase-space, it eventually folds onto itself leading to a formation of a winding pattern, which resembles a spiral for orbits close to circular. Such a phase-space spiral was uncovered recently in the disc stars around the Sun and is believed to be produced by a relatively recent perturbation of the Galactic disc by a massive body (see Antoja et al. 2018). For a highly eccentric GS/E-like merger, this phase-mixing manifests most clearly in Galactocentric spherical polar (vr , r) space as a series of nested chevrons (chevron is a projection of the sheet onto this sub-space), but topologically are nonetheless a spiral, albeit severely distorted (e.g., fig. 6 of Quinn (1984) and section 8.5 of Binney & Tremaine (2008)). Please see Dong-Paez et al (2022) for a detailed description of the formation and evolution of the Galactic mille-feuille.

Most recently, Belokurov et al (2023) showed that such nested chevrons created as a result of phase-mixing of the GS/E stellar debris could indeed be seen using the Gaia Data Release 3 data. Following this discovery, Davies et al (2023) demonstrated that DM sub-halos were bound to interact with the stars in the chevrons thus disturbing their coherence. They have come up with a statistic to quantify the amount of perturbation and tested it using N-body simulations of DM sub-halos interacting with a realistic GS/E debris cloud composed of a large number of narrow chevrons. When modelling the effects of repeated interactions with multiple low-mass sub-halos, Davies et al 2023 hit a stumbling block - the time to compute all interactions turned out to be too large. Therefore, they have only computed the effects of repeated encounters with DM sub-halos above 10^7 Solar (see Fig 1). The aim of this Project is to extend the analysis of Davies et al (2023) into lower masses and find the sensitivity limit of the Galactic mille-feuille. In addition, more realistic simulations of the subhaloes themselves could help better determine how sensitive the mille-feuille is to them. Davies et al (2023) considered the subhaloes to be on unchanging orbits of test particles, rather than N body particles. This change may not be too difficult to implement.

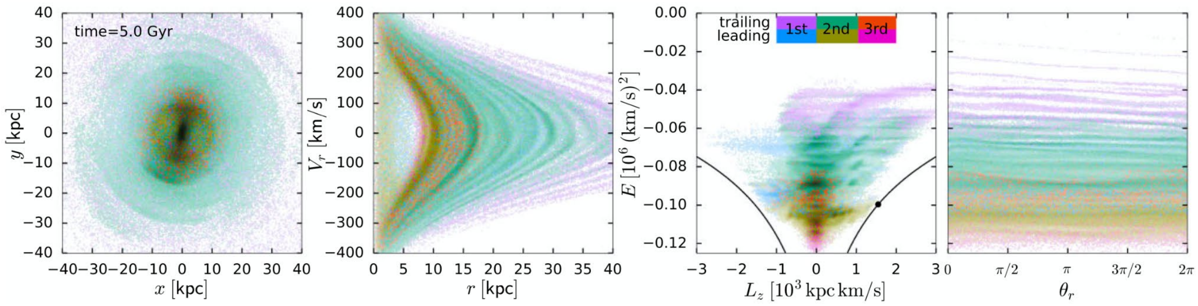

Figure 1.: Tailored N-body merger simulation different views.This is the snapshot of the merger at 5 Gyr from the start of interaction. Left-most column shows the spatial distribution of the debris, second column shows the r–vr phase-space, third panel presents the E–Lz space, and the right-most one shows E versus the radial phase angle θr. Particles are coloured by their stripping episode and the location in the leading or trailing arms at the time of unbinding from the satellite. In the third column, black lines delineate the angular momentum of a circular orbit, and black dot marks the fiducial Solar location in this space. This is the reproduction of Figure 12 from Belokurov et al (2023).

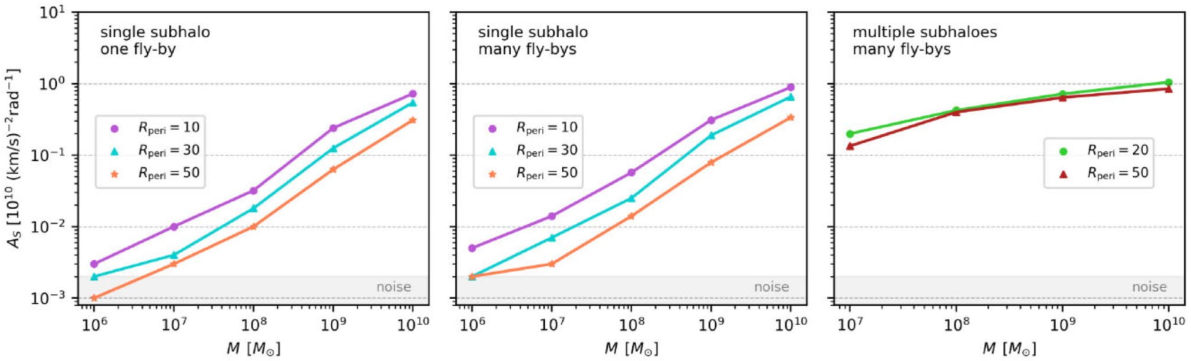

Figure 2.: Strength of mille-feuille perturbation as a function of the DM perurtber's mass. Note that in the first two panels the signal drops to the noise level (horizontal grey band) around $M=10^6$ Solar. However, in the right-most panel, the calculation is only performed down to $M=10^7$ Solar where it is significantly above the noise level, and importantly, shows a very shallow decay to low masses. This is a reproduction of Figure 11 from Davies et al 2023.

Project Details

The Project will start with a set of experiments designed to reproduce the results of Davies et al (2023) – simple orbital modelling of one subhalo, the simulation of populations of subhaloes, and the simulation of the GS/E merger itself. The original GS/E merger simulation is available and can/will be provided. The simulations of interactions between DM sub-halos and the stars in the GS/E merger debris are carried out using the AGAMA orbital integration and galaxy modelling package, which has an easy-to-use Python interface (Vasiliev 2019; see the AGAMA website: agama.software).

The student will construct a set-up whereby they explore the sensitivity of the GS/E debris to sub-halo interactions of various sensible masses and eventually below the 10^7 Solar mass limit hit in Davies et al (2023). This may involve simply modifying the original code used in Davies et al (2023), writing a new version of the interaction code, coming up with an analytical approximation, and/or using high performance computing resources. The way in which we have previously *quantified* the subhalo perturbations also has room for improvement if the student wishes to develop an alternative method.

The project can be extended in several ways. First, in addition to measuring the amount of perturbation in the simulation the student can try to come up with a way of detecting and characterising the perturbations in the *observations*. This allows the student to get hands-on with real *Gaia* data to develop their data analysis skills, as well as developing fundamental orbital simulation skills. Second, it would be useful to understand if the perturbations induced by massive DM subhalos can be distinguished from those caused by low-mass ones; do the perturbations induced by a population of low mass subhaloes differ from the perturbations of one high mass subhalo in some distinct way? Last but not least, the student could study the survivability of the mille-feuille itself in the busier inner Milky Way. For example, it may be important to understand the impact of baryonic sub-structure in the MW disc on the sheets of the mille-feuille.

Before any simulations begin, the student may wish to begin by familiarising themselves with the relevant background theory. Most important are the process of phase mixing and action-angle variables, which play a key role in the methods developed in Davies et al (2023), and in orbital integration more generally.

Skills Required

Desirable: Python. Optional: AGAMA.

Lecture Courses: Part II Stellar Dynamics and Structure of Galaxies. Part III - Life and Death of Galaxies

Useful References (List of important papers/review articles relevant to the project)

- Belokurov et al (2023) https://ui.adsabs.harvard.edu/abs/2023MNRAS.518.6200B/abstract
- Davies et al (2023) https://ui.adsabs.harvard.edu/abs/2023MNRAS.519..530D/abstract
- Dong-Paez et al (2022) https://ui.adsabs.harvard.edu/abs/2022MNRAS.510..230D/abstract

Project 32: The nearby population of young stars as revealed in Hα by Gaia

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Project Summary

The population of Young Stellar Objects (YSOs) in the Solar neighbourhood has been studied for decades and still continues to be updated thanks to new observations and wider surveys. Recently, the Gaia mission has produced the most detailed 3D map of stars in the Galaxy, which has already resulted in significant updates to the memberships of nearby star-forming regions.

Gaia also provides low-resolution spectra, a resource that is just becoming public and is currently vastly unexplored. This project will use these spectra to identify nearby sources showing emission from the H-alpha line, characteristic of active, young (and sometimes accreting) stars. The identified H-alpha emitters will represent the first all-sky, 3D view of the solar neighbourhood which, combined with Gaia distances, will provide an unprecedented view of nearby star formation. This sample can then be compared with the known populations of young stars, improving our understanding of them and possibly revealing new members, young, isolated sources, and maybe even new associations.

Background

The population and distribution of YSOs in the Galaxy has been traditionally studied using different youth indicators such as predicted photospheric colours, stellar activity, certain spectroscopic lines (e.g., H-alpha, lithium), or the presence of infrared excess due to circumstellar disks. Memberships to these associations have been increasingly refined as additional data become available, identifying new members and removing foreground/background contamination.

The Gaia mission brought a major update to these studies by creating the most detailed 3D map of the Galaxy, measuring not only distances but also proper motions for over a billion stars. With this new information, memberships to different associations have been revisited based on clustering properties (e.g., Zucker et al. 2020, Luhman & Esplin 2020), and precise Gaia distances have also been instrumental in the identification of isolated, young massive stars (e.g., Vioque et al. 2018, 2020).

The Gaia mission also obtained low-resolution spectra of all the observed sources. This new resource, which has recently become public, is vastly unexplored and hosts the potential for a large number of new studies. This project will be the first all-sky spectroscopic survey of YSOs in the Solar neighbourhood.

Project Details

This project will exploit new low-resolution spectra of stars published in the Gaia Data Release 3 to search for H-alpha emitters in all Gaia sources within 500 pc from the Sun. The H-alpha line is typically observed in emission in YSOs due to stellar activity and/or accretion of material from protoplanetary disks and is regarded as a clear indication of youth.

The project consists of three main steps:

1. Compilation of the spectra of all the Gaia sources within 500 pc (over 9 million sources) and search for the H-alpha line in emission. We will use the Gaia archive to retrieve the corresponding spectra and use a software specifically developed to identify lines in Gaia spectra (Weiler et al. 2023, see Fig. 1).
2. Data exploration and identification of contaminants. Given the large samples involved and the exploratory nature of the project, we are guaranteed to encounter false positives and misclassified sources. We will rely on the precise distance estimates from Gaia and a combination of additional indicators (location in the HR diagram, presence of IR excess) to build a sample of bona fide nearby YSOs with H-alpha emission.
3. Analysis of the resulting sample of nearby YSOs. We will compare the identified YSOs with the currently known populations of star-forming regions and search for potential new members. We may also identify isolated YSOs, either due to ejection from the molecular cloud where they formed or because of their formation process. This process may even identify new associations.

Overall, the project will produce the first complete spectroscopic analysis of the H-alpha line in the Solar neighbourhood, assessing the biases currently present in all population studies of the disk and accretion properties of forming stars. This updated sample of young stars will improve our understanding of star formation rates in nearby regions and allow us to derive updated disk fractions in molecular clouds. Moreover, this will be one of the first works using Gaia spectra, and it will place us in a fantastic position to further exploit this resource in future studies.

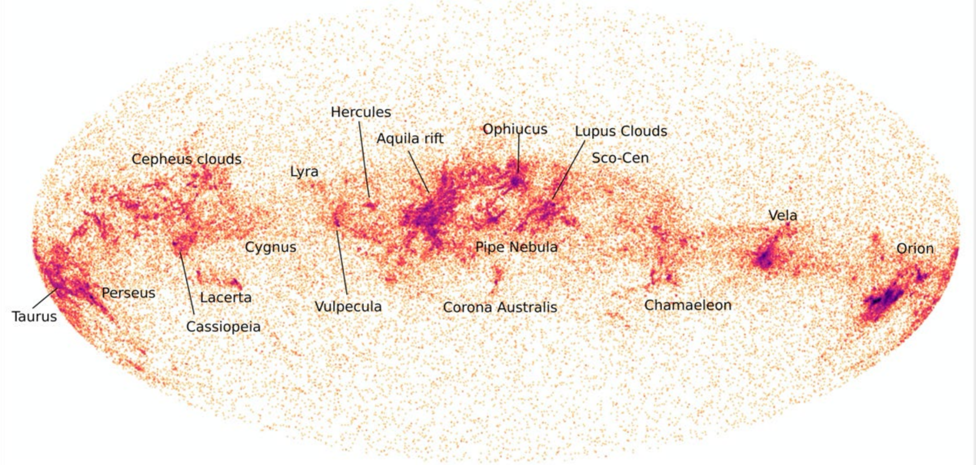

Figure 1.:Distribution of young stars in the galaxy with ages < 20 Myr (Zari et al. 2018). This map was produced using a combination of photometric data and Gaia distances from the Gaia Data Release 2. However, photometrically-selected samples of YSOs are known to suffer from significant contamination. The proposed Part III project will improve upon this map by searching at the H alpha emission line in the Gaia DR3 low-resolution spectra.

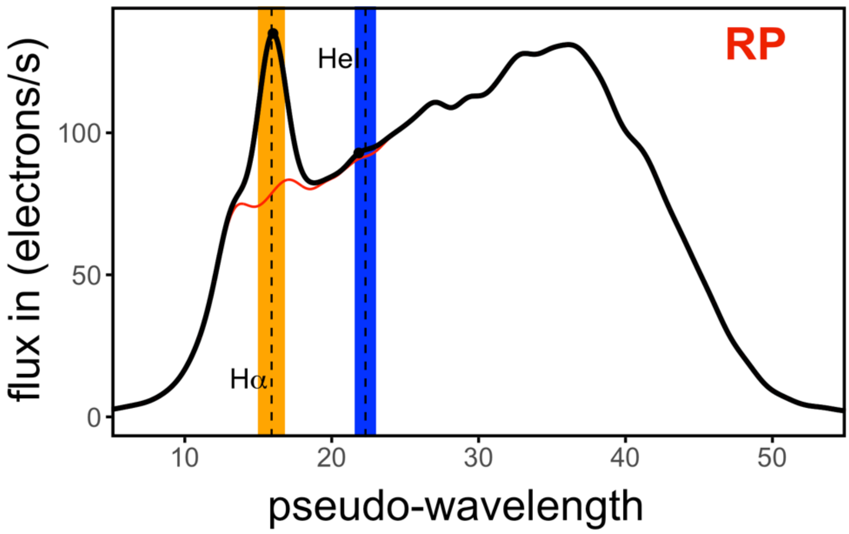

Figure 2.: Example of a Gaia spectrum with H-alpha emission and its identification using the method in Weiler et al. (2023). In this project, the same methodology will be applied to millions of stars in the Solar neighbourhood.

Skills Required

- Programming experience, ideally in Python or PostgreSQL.
- A background in Astrophysics, in particular young stars and/or protoplanetary disks (for example the Part II courses "Introduction to Astrophysics", "Structure and Evolution of Stars", or "Astrophysical Fluid dynamics"), is desirable.

General References (List of papers referred to in the project)

- Zucker et al. 2020, A compendium of distances to molecular clouds in the Star Formation Handbook, https://ui.adsabs.harvard.edu/abs/2020A%26A...633A..51Z/abstract
- Luhman & Esplin 2020, Refining the Census of the Upper Scorpius Association with Gaia, https://ui.adsabs.harvard.edu/abs/2020AJ....160...44L/abstract
- Vioque et al. 2018, Gaia DR2 study of Herbig Ae/Be stars, https://ui.adsabs.harvard.edu/abs/2018A%26A...620A.128V/abstract
- Vioque et al. 2020, Catalogue of new Herbig Ae/Be and classical Be stars. A machine learning approach to Gaia DR2, https://ui.adsabs.harvard.edu/abs/2020A%26A...638A..21V/abstract
- Weiler et al. 2023, Analysing spectral lines in Gaia low-resolution spectra, https://ui.adsabs.harvard.edu/abs/2023A%26A...671A..52W/abstract

Project 33: Populations of massive stars in the Local Group

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UTO: Christopher Tout (cat@ast.cam.ac.uk) - until December 2023

Avishai Gilkis (ag2017@cantab.ac.uk) - from Jan 2024

Project Summary

Detailed observations of massive stars in nearby galaxies provide critical tests of stellar evolution theory. One such test is the empirical upper luminosity boundary of cool supergiant stars, known as the Humphreys-Davidson limit, which is in tension with stellar evolution predictions. A possible resolution for this tension is that such over-luminous stars are simply statistically unlikely, though this possibility must be tested quantitatively. In this project detailed stellar evolution simulations will be used to generate synthetic populations that will be compared to observed populations of massive stars in nearby galaxies to ascertain how well theory can explain the observations. The population synthesis will be done with variations in the star-formation history and other initial properties to test their effect on the tension between theory and observations.

Background

Massive stars, with a mass initially above about eight times that of the sun, are short-lived and rare, but have a significant contribution to several important astrophysical phenomena, such as stellar nucleosynthesis and core-collapse supernovae. Neutron stars and black holes are generally considered to be formed through the collapse of an iron core of a massive star, and in binary systems they can become sources of gravitational waves originating from merging black holes, or kilonova explosions resulting from merging neutron stars that might be the origin of the heaviest elements in the Universe.

The evolution of massive stars, and therefore their ultimate fate, is plagued by several uncertainties. These include processes such as mixing in stellar interiors and mass loss by stellar winds. Furthermore, most massive stars are born in close binary systems, and the interaction with a companion can significantly alter the evolution and fate of a massive star. Comparisons between observations and theoretical predictions provide crucial tests of our understanding of stellar evolution theory.

Populations of massive stars in Local Group galaxies are favourable for comparing observations with theory, as they are close enough for individual stars to be resolved, while suffering less dust extinction and distance uncertainty compared with massive stars in the Milky Way. In the Magellanic Clouds, the populations of evolved massive stars are considered to be observationally complete (see Figure 1 for the Large Magellanic Cloud). We will test population models for the massive stars in the Magellanic Clouds and other nearby galaxies and make detailed comparisons with the observational data.

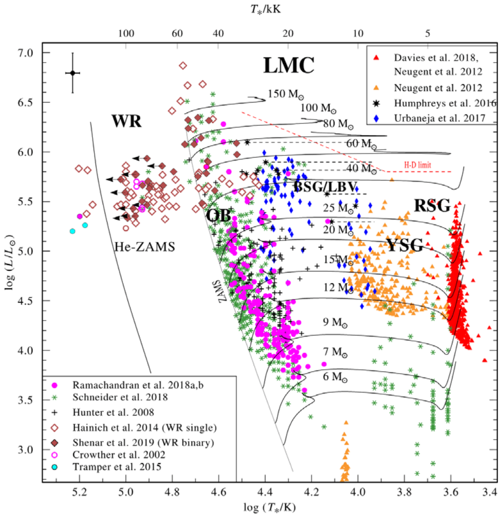

Figure 1.: Populations of massive stars in the Large Magellanic Cloud compared with stellar evolution tracks (from [1]).

Project Details

The student will generate synthetic populations of massive stars based on detailed stellar evolution simulations and compare them to observational data. This will be done by using a code that will be developed by the student. The code will use pre-computed stellar evolution models of single and binary stars, and the population synthesis will be done by random sampling of the tracks according to assumed distributions of initial conditions such as the initial mass function and the star-formation history. The initial project plan will be as follows:

1. Develop a simple synthetic population generation code.
2. Compare synthetic populations generated from single stars with synthetic populations including binary stars.
3. Compare synthetic populations generated using a constant star-formation rate with synthetic populations using a complex star-formation history (as is assumed to be the case for example in the Small Magellanic Cloud, see Figure 2).
4. Compare the synthetic populations generated with various assumptions to the observed populations in Local Group galaxies, in particular the Magellanic Clouds, M31 and M33.

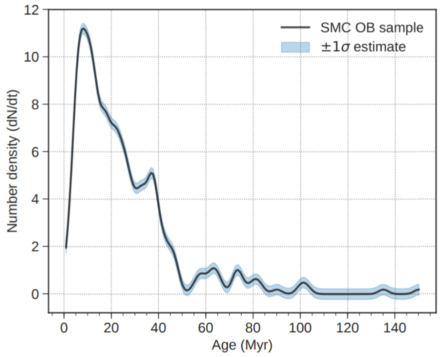

Figure 2.: Distribution of stellar ages in the Small Magellanic Cloud (from [2]).

Skills Required

Experience coding with Python will be useful. Some knowledge of stellar evolution is essential. The part-II course on Structure and Evolution of Stars suffices but the part-III course is desirable.

Useful References (List of important papers/review articles relevant to the project)

- "The luminosities of cool supergiants in the Magellanic Clouds, and the Humphreys-Davidson limit revisited", Davies et al., 2018, MNRAS, 478, 3138;
- "The Red Supergiant Content of M31 and M33", Massey et al., 2021, AJ, 161, 79

General References (List of papers referred to in the project)

- [1] “The excess of cool supergiants from contemporary stellar evolution models defies the metallicity-independent Humphreys-Davidson limit”, Gilkis et al., 2021, MNRAS, 503, 1884; [2] "Testing massive star evolution, star formation history, and feedback at low metallicity.
- Spectroscopic analysis of OB stars in the SMC Wing", Ramachandran et al., 2019, A&A, 625, 104

Project 34: Evolution of hydrogen-deficient binary stars

Supervisor I: Avishai Gilkis (ag2017@cantab.ac.uk)

UTO: Christopher Tout (cat@ast.cam.ac.uk) - until December 2023

Avishai Gilkis (ag2017@cantab.ac.uk) - from Jan 2024

Project Summary

Hydrogen-deficient binaries are a rare type of stellar system, with only a handful known in our Galaxy. Understanding them can shed light on binary evolution processes, such as mass transfer, which are important for many stellar types and especially massive stars which are mostly born in close binaries. The brightest and most well-studied hydrogen-deficient binary is upsilon Sagittarii, though even this case is not satisfactorily explained by theory. In this project binary evolution will be simulated with a stellar evolution code to model the upsilon Sagittarii system and other hydrogen-deficient binaries, focusing on the angular momentum evolution of the systems and their individual stellar components.

Background

Stellar binary interaction can lead to many interesting astrophysical phenomena, from chemical peculiarities in stellar compositions to nova and supernova explosions. Yet, some aspects of binary evolution are poorly understood. One outstanding problem is the question of mass transfer efficiency. I.e., when a star expands so that it loses material through the process of Roche-lobe overflow (RLOF), how much of that material is accreted by the companion star and how much is lost from the binary system? Simple angular momentum considerations predict that a small mass gain will spin up the accreting star to critical rotation and prohibit further mass gain [1]. However, blue straggler stars [2] and Algol-type binary stars indicate that a significant mass gain does take place, and a similar conclusion was reached from a recent analysis of the hydrogen-deficient binary upsilon Sagittarii (Figure 1). A possible resolution for these contradicting mass transfer efficiency paradigms is that angular momentum can be removed from the accreting star by magnetic fields [3], enabling a significant mass gain while avoiding critical rotation. The mass transfer efficiency and angular momentum evolution can affect various stellar phenomena related to binary systems, and different modelling approaches should be tested with observations.

Project Details

The student will simulate stellar evolution scenarios for hydrogen-deficient binaries. The simulations will then be used to find best-fitting models for observed systems such as upsilon Sagittarii and for deriving more general properties of hydrogen-deficient stars. The initial project plan will be as follows:

1. Learn to use a stellar evolution code and interpret the simulation results.
2. Run non-rotating binary star models and find a best-fitting scenario for upsilon Sagittarii.
3. Run rotating binary star models and check the limits of mass gain because of spin up.
4. Code a module to be incorporated in the simulations that removes angular momentum and allows significant mass gain in rotating models.

5. Use the models to derive theoretical properties of hydrogen-deficient binaries, such as the duration of the hydrogen-deficient phase of the primary, and the rotation of the secondary.

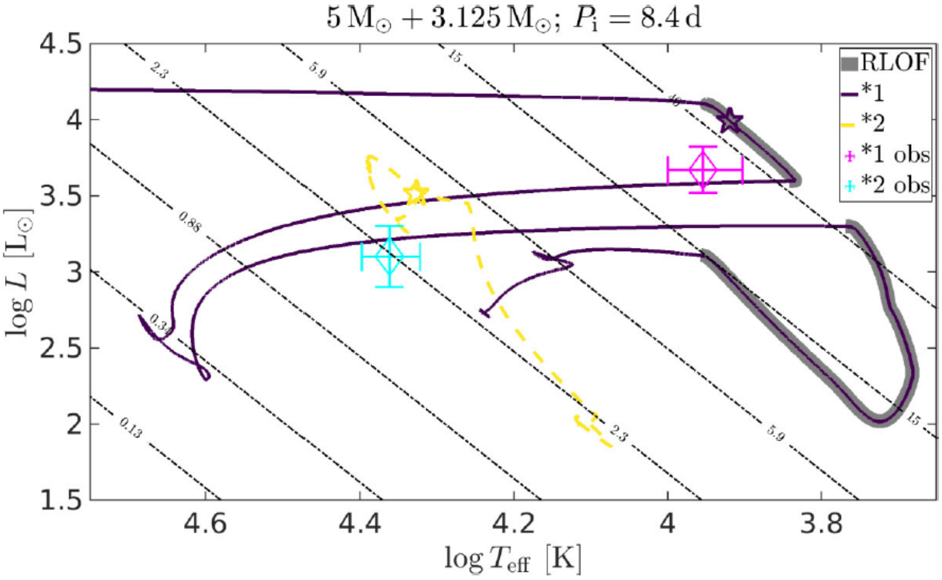

Figure 1.: Binary evolution scenario for upsilon Sagittarii (from [4]).

Skills Required

- Basic coding skills with Python and Fortran will be useful.
- Some knowledge of stellar evolution is essential.
- The part-II course on Structure and Evolution of Stars suffices but the part-III course is desirable.

Useful References (List of important papers/review articles relevant to the project)

- "TESS uncloaks the secondaries in hydrogen-deficient binaries", Jeffery, 2023, MNRAS, 518, L75

General References (List of papers referred to in the project)

- [1] “On the spin-up of the mass accreting component in a close binary system”, Packet, 1981, A&A, 102, 17; [2]
- "Stars acquire youth through duplicity", Tout, 2011, Nature, 478, 331; [3] "Spin angular momentum evolution of the long-period Algols", Dervişoğlu et al., 2010, MNRAS, 406, 1071; [4]
- "Ups!... I did it again: unveiling the hidden companion in Upsilon Sagittarii, a unique binary system at a second mass transfer stage", Gilkis & Shenar, 2023, MNRAS, 518, 3541

Project 35: Climate stability of tenuous CO2 atmosphere

Supervisor I: Sean Jordan (saj49@cam.ac.uk)

UTO: Oliver Shorttle (oshorttle@ast.cam.ac.uk)

Project Summary

When interpreting observations of exoplanets, there is a degeneracy between terrestrial planets with a thick (Venus-like) CO2 atmosphere and reflective cloud layer, versus a thin (Mars-like) CO2 atmosphere over a reflective icy surface. In this project, we aim to map out where these two regions of climate stability overlap.

Background

In the Solar System, Venus and Mars possess atmospheres dominated by CO2. Mars is less massive and therefore less able to hold onto a substantial atmosphere compared to Venus. For exoplanets around low mass stars, it is unclear whether planets as massive as the Earth/Venus and even greater in mass, will hold onto a substantial atmosphere or not due to enhanced stellar activity compared to the Sun (Scalo et al., 2007). Current observations of rocky planets around low mass host stars will aim to determine whether such planets have atmospheres and how substantial they are (Greene et al., 2023; Zieba et al., 2023). The signals obtained from rocky planets are relatively small and interpreting these limited observations is complicated by the degeneracy of possible states that can be consistent with the observations. It has been demonstrated that observations of a Venus-like planet can, in some cases, be equally well explained by a planet with a reflective icy surface and only a tenuous atmosphere (Konrad et al., 2023). It remains to be demonstrated where the latter case is theoretically possible and therefore which observational targets will be susceptible to this degeneracy (one specific example is plotted in Figure 1. where a is surface albedo). The results of this modelling exercise will lay down a roadmap which current and future observations can test empirically.

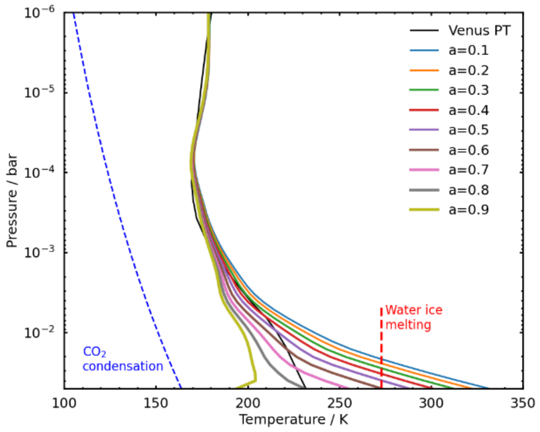

Figure 1.: Pressure-temperature profiles in the atmosphere of a Venus-sized planet with a 0.05 bar CO2 atmosphere and an icy surface. For a Venus-equivalent isolation flux, only sufficiently high surface albedos (a) can keep the surface below the water ice melting temperature, therefore stabilising the climate. Comparing the range of required surface albedos to the cloud albedo of a planet which instead possesses a thick CO2 atmosphere and global cloud layer can reveal whether these two cases are observationally degenerate or distinguishable.

Project Details

The project will use a recently developed climate code to simulate the 1D temperature profiles of exoplanets. The code has been developed from the Planetary Climate Module found online at: https://github.com/wordsworthgroup/mars_redox_2021/tree/main/PCM_LBL. The code computes opacities of molecules in a planets atmosphere, and uses this to calculate the planet's temperature structure based on the irradiating stellar spectrum and the atmospheric composition. Simulations will be performed across a range of orbital distances, surface albedos, and planetary masses, for various types of host stars. The temperature profiles will be compared to the condensation curves of CO2 and H2O and regions of climate stability will be determined.

Skills Required

- Programming in python. Programming in Fortran helpful but not essential.
- Relevant lecture courses include:
    - Part II Structure and Evolution of Stars,
    - Part III Exoplanet atmospheres and interiors.

Useful References (List of important papers/review articles relevant to the project)

- Zahnle and Catling. The Cosmic Shoreline: The Evidence that Escape Determines which Planets Have Atmospheres, and what this May Mean for Proxima Centauri B. ApJ 843 122 (2017). doi:10.3847/1538-4357/aa7846
- Jacob Lustig-Yaeger et al. A Mirage of the Cosmic Shoreline: Venus-like Clouds as a Statistical False Positive for Exoplanet Atmospheric Erosion. ApJL 887 L11 (2019). doi:10.3847/2041-8213/ab5965
- Vidaurri et al. The Outer Edge of the Venus Zone around Main-sequence Stars. Planet. Sci. J. 3 137 (2022). doi:10.3847/PSJ/ac68e2

General References (List of papers referred to in the project)

- Scalo et al. M Stars as Targets for Terrestrial Exoplanet Searches And Biosignature Detection. Astrobiology 85-166 (2007). doi:10.1089/ast.2006.0125
- Greene, T.P., et al. Thermal emission from the Earth-sized exoplanet TRAPPIST-1b using JWST. Nature 618, 39–42 (2023). doi:10.1038/s41586-023-05951-7
- Zieba, S., et al. No thick carbon dioxide atmosphere on the rocky exoplanet TRAPPIST-1 c. Nature (2023). doi:10.1038/s41586-023-06232-z
- Konrad et al. Large Interferometer For Exoplanets (LIFE) - IX. Assessing the impact of clouds on atmospheric retrievals at mid-infrared wavelengths with a Venus-twin exoplanet. A&A, 673 (2023) A94. doi:10.1051/0004-6361/202245655

Project 36: Complex interplay of stellar and AGN feedback in simulated galaxies

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Supervisor II: Eun-jin Shin (shinej816@snu.ac.kr)

Supervisor III: Martin Bourne (mabourne@ast.cam.ac.uk)

Supervisor IV: Sophie Koudmani (sk939@cam.ac.uk)

UTO: Debora Sijacki (deboras@ast.cam.ac.uk)

Project Summary

In this project a systematic study of stellar and black hole feedback processes will be performed by running high-resolution simulations of disc galaxies, embedded within dark matter haloes with a mass of 1010M⨀ to 1013M⨀. State-of-the-art models for resolved interstellar medium (ISM; Smith et al., 2018-2021b) and black hole accretion and feedback (Koudmani et al., 2019, 2022, Bourne et al., in prep.) will be employed within the moving mesh code AREPO (Springel et al., 2010, Weinberger et al., 2019).

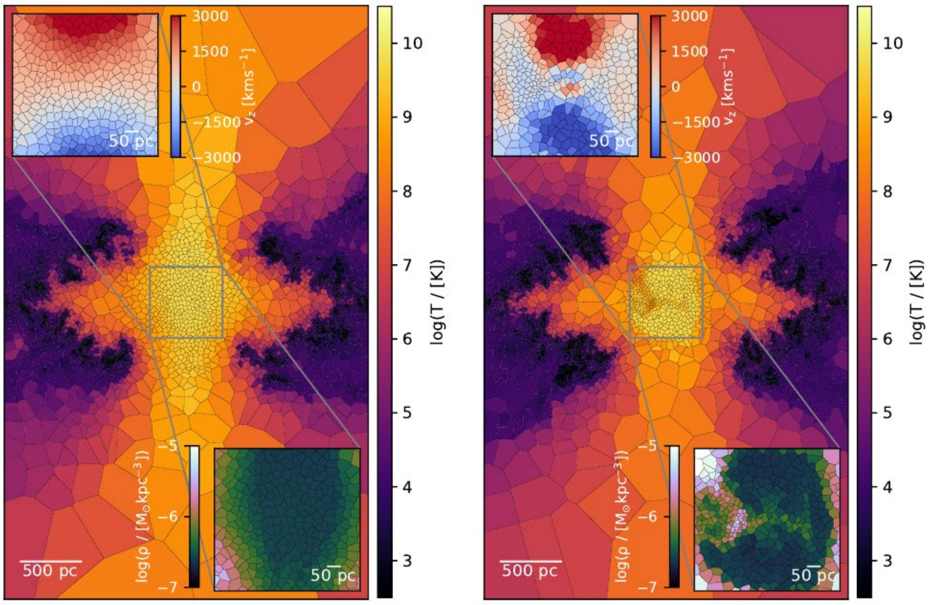

Figure 1.: Edge-on projections of the Voronoi mesh (3.0 × 5.0 × 0.2 kpc) for the two different AGN injection models at t ~ 25 Myr. The left panel shows the isotropic, thermal feedback scheme, and the right panel shows the bipolar, mass-loaded outflows. The colour coding in the main panels indicates the gas temperature and the colour coding in the two insets indicates the vertical gas velocity and gas density, respectively (Koudmani et al., 2019).

The project aims to understand which physical processes shape key galaxy properties, such as star formation rate, stellar mass, and galactic outflows, as well as the thermodynamics and chemistry of the circumgalactic medium (CGM).

Background

The ISM is a complex multiphase medium, with the intertwined processes of star formation and stellar feedback playing a major role in determining galaxy properties. Moreover, there is growing observational evidence, both at high redshifts and in the local Universe, that feedback from active galactic nuclei (AGN), in the form of winds, jets or radiation not only plays a key role in massive, elliptical galaxies but could be an important ingredient for all galaxy types, including the smallest galaxies, the so-called dwarfs. Recent SDSS/MANGA, MUSE and JWST observations are giving us an unprecedented view of the ISM properties as well as AGN feedback-induced changes in the ISM thermodynamics and kinematics (Emsellem et al., 2022, Lee et al., 2023, Cresci et al., 2023, Cresci et al., 2018, Aravindan et al., 2023). High resolution simulations, with spatially resolved ISM phases, are crucial in this respect to unveil and understand the physical processes that drive the observed galaxy population (Mercedes-Feliz et al., 2023, Wellons et al., 2023, Sivasankaran et al., 2022, Dubois et al., 2021).

Project Details

In this project, the massively parallel, moving mesh code AREPO with be used, together with the latest implementation of resolved ISM (Smith et al., 2018-2021b) and a model for black hole accretion and accretion-disk-driven winds (Koudmani et al., 2019, 2022, Bourne et al., in prep.). The initial conditions of galaxies embedded in a CGM will be provided, and the student is expected to run the simulations on our local HPC facilities in Cambridge (https://www.hpc.cam.ac.uk/high-performance-computing). Initially, the project will focus on a single Milky Way-like galaxy, where the main task will be to analyse the simulations and physically understand which processes drive the simulated star formation rates, colours, ISM kinematics, galaxy outflow rates, CGM enrichment etc. Also, emphasis will be placed on studying AGN fuelling and AGN feedback on the ISM and CGM. Depending on the progress, additional simulations may be performed varying for example the initial gas fraction in the galactic disc as well as considering galaxies of different masses, to be able to constrain the relative importance of feedback processes as a function of the halo mass.

Skills Required

- The student should be keen on programming and have a good knowledge of C and Python.
- The Part II courses “Astrophysical Fluid Dynamics” and “Stellar Dynamics and Structure of Galaxies” are required.

Useful References (List of important papers/review articles relevant to the project)

- Binney & Tremaine, Galactic Dynamics, Princeton University Press, Princeton, NJ USA, 2008
- Kormendy & Ho, 2013, https://arxiv.org/abs/1304.7762
- Volonteri et al., 2010, https://arxiv.org/abs/1003.4404
- Vogelsberger et al., 2020, https://arxiv.org/abs/1909.07976
- Naab et al., 2017, https://arxiv.org/abs/1612.06891
- Somerville et al., 2015, https://arxiv.org/abs/1412.2712
- Robertson et al., 2022, https://arxiv.org/abs/2110.13160

General References (List of papers referred to in the project)

- Weinberger et al., 2019, https://arxiv.org/abs/1909.04667 (see also: https://arepo-code.org/wp-content/userguide/index.html)
- Springel et al., 2010, https://arxiv.org/abs/0901.4107
- Koudmani et al., 2022, https://arxiv.org/abs/2206.11274
- Koudmani et al., 2019, https://arxiv.org/abs/1812.04629
- Smith et al., 2021a, https://arxiv.org/abs/2010.10533
- Smith et al, 2021b, https://arxiv.org/abs/2009.11309
- Smith et al., 2019, https://arxiv.org/abs/1807.04288
- Smith et al., 2018, https://arxiv.org/abs/1709.03515
- Emsellem et al., 2022, https://arxiv.org/abs/2110.03708
- Lee et al., 2023, https://arxiv.org/abs/2212.02667
- Cresci et al., 2023, https://arxiv.org/abs/2301.11060
- Cresci et al., 2018, https://arxiv.org/abs/1802.10305
- Aravindan et al., 2023, https://arxiv.org/abs/2304.04737
- Mercedes-Feliz et al., 2023, https://arxiv.org/abs/2301.01784
- Wellons et al., 2023, https://arxiv.org/abs/2203.06201
- Sivasankaran et al., 2022, https://arxiv.org/abs/2203.14985
- Dubois et al., 2021, https://arxiv.org/abs/2009.10578

Project 37: Shaking up planetary systems in globular clusters

Supervisor I: Cathie Clarke (cclarke@ast.cam.ac.uk)

Supervisor II: Andrew Winter (andrew.winter@oca.eu)

Supervisor III Mark Wyatt (wyatt@ast.cam.ac.uk)

UTO: Cathie Clarke (cclarke@ast.cam.ac.uk)

Project Summary

Globular clusters are ancient and extremely dense systems where any planets, if formed, are likely to have been dynamically sculpted by interactions with passing stars. This process has been extensively examined in the case of the globular cluster 47 Tucanae (Figure 1) where simulations suggest that dynamically perturbed planets formed at a few AU can give rise to a substantial population of planets in small separation orbits (hot Jupiters), as well as numerous instances of planets plunging into their parent stars. These calculations were however based on simplified expressions for the way that planetary eccentricity is pumped up by encounters. This project will test these expressions by performing large numbers of dynamical simulations involving a star and orbiting planet and the flyby of a neighbouring star, checking changes in planetary eccentricity for a range of encounter parameters. The aim of the project is to improve predictions of the evolution of planetary orbits in globular clusters. With ongoing plans to search for hot Jupiters in globular clusters, such predictions can be used to invert the problem, i.e., deduce the properties of planets at birth from the present day statistics of hot Jupiters detected in clusters.

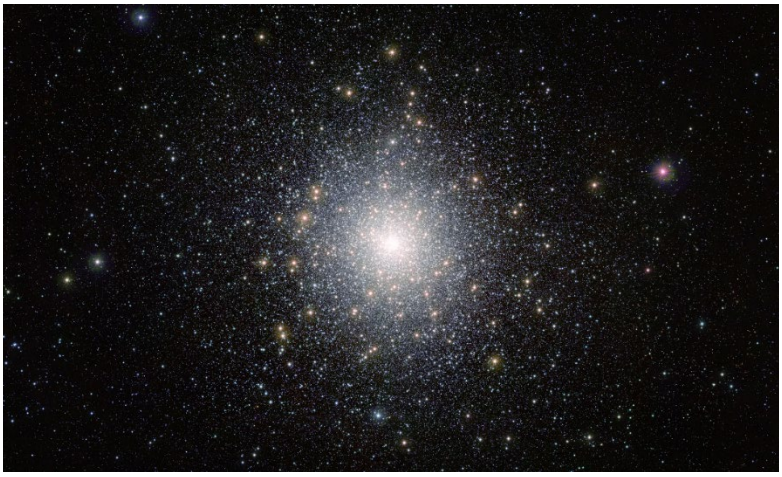

Figure 1.: The globular cluster 47 Tucanae observed by the VISTA telescope. Its high density and stellar velocity dispersion implies that planetary systems will be substantially shaken up by the effect of encounters with neighbouring stars. This project will improve the accuracy of modelling this process and will thus help connect the original orbital properties of planets in 47 Tucanae to their potentially observable properties today, following 10 Gyr of dynamical evolution.

Background

The conditions in Globular Clusters would have been very different at the time that they formed (> 10 Gyr ago) compared with the conditions found in present day local star forming regions. Notably the metallicity was significantly lower and the stellar density significantly higher than the local star forming clouds that are the sites of ongoing planetary system formation at current epochs. The existence of planets in globular clusters has not yet been established, in part due to discouragement following the failure of Gilliland et al 2000 to detect transiting planets in their relatively shallow transit survey in the globular cluster 47 Tuc (Gilliland et al 2000); observational interest is however rekindling (Grunblatt et al 2023) along with theoretical efforts to understand how planetary systems should evolve in globular clusters. In particular, a number of papers (Hamers & Tremaine 2017, Rodet et al 2021, Winter et al 2022,2023) have explored the way that planetary systems are shaken up as a result of dynamical stirring by flybys of neighbouring stars in the dense core of the cluster. Such interactions excite significant eccentricity in planetary orbits with the result that a gas giant planet formed at 5 AU (Jupiter's orbital radius) in the core of a globular cluster may end up as a hot Jupiter (tidally circularised close to the host star) or even be swallowed by the star. Each of these outcomes may generate observational signatures (planetary transits in the case of hot Jupiters and possible stellar abundance anomalies in the case of star-planet mergers). Provided there is a good dynamical model for eccentricity excitation in planetary environments, such observational signatures can be used to constrain the original population of gas giants on wider (5-10 AU) orbits in globular clusters.

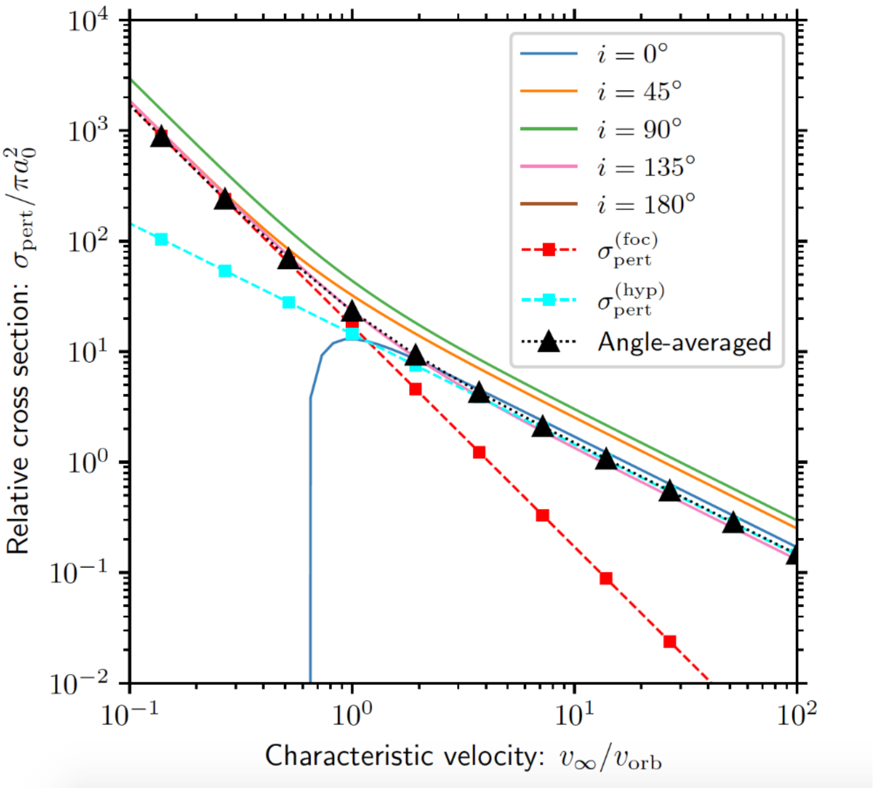

Figure 2.:. **The ratio of the cross-section for encounters leading to a fixed eccentricity change of a planet in an orbit with e=0.9 to the geometrical cross section of the orbit, plotted as a function of the ratio of the velocity of the perturber at infinity to the orbital velocity of the planet (from Winter et al 2022). These cross sections were evaluated using analytic formulae from Heggie & Rasio 1996 which need to be checked and corrected through a set of numerical calculations of stellar flybys in planetary systems.**

Project Details

The purpose of this project is to use dynamical simulations to check analytical expressions for the excitation of eccentricity during stellar flybys. These analytical expressions (originally derived by Heggie & Rasio 1996) involve two crucial assumptions:

i. they only consider quadrupole terms in the expansion of the gravitational potential induced by the perturber, and

ii. they are evaluated in the slow (tidal) limit where the flyby is significantly longer in duration than the orbital period of the planet and hence the gravitational forces on the planetary orbit can be calculated by averaging its mass distribution around its orbit.

Winter et al 2022 used these expressions to calculate cross-sections for eccentricity excitation and argued that the hyperbolic limit was most relevant to conditions in globular clusters. These authors then fed these hyperbolic cross sections into a diffusion equation describing the evolution of planetary eccentricity over long timescales. In this project, the student will instead calculate the cross-sections for excitation of planetary eccentricity from dynamical simulations using the REBOUND N-body code (Rein & Liu 2012). In the process they will define the limits of applicability of the Heggie & Rasio expressions and determine which are the dominant regimes which need to be considered in the globular cluster context. The outcome of the project will thus be a more robust description of the evolution of planetary eccentricity in globular clusters.

Skills Required

- The project will require programming using the REBOUND code which is most conveniently run from a python module. Thus, knowledge of python is an advantage though those with other programming experience should soon develop the necessary skills.
- A background in stellar dynamics, for example, the Part II courses “Stellar Dynamics and Structure of Galaxies” is desirable as is following of the Part III course `Planetary System Dynamics.’

Useful References (List of important papers/review articles relevant to the project)

- Forming short period substellar companions in 47 Tucanae: II Analytical Expressions for the Orbital Evolution of Planets in dense environments. Winter, A. et al 2022. MNRAS 515,2837
- The effect of encounters on the eccentricity of binaries in clusters. Heggie, D., Rasio, F., 1996 MNRAS 282,1064
- REBOUND: An open-source multi-purpose N-body code for collisional dynamics. Rein, H., Liu, S., A & A 537,A128

General References (List of papers referred to in the project)

- Roman CC White Paper: Adding Fields Hosting Globular Clusters to the Galactic Bulge Time Domain Survey (Grunblatt, S. et al 2023: https://arxiv.org/pdf/2306.10647
- Hot Jupiters driven by high-eccentriciy migration in globular clusters. Hamers, A., Tremaine, S., 2017. MNRAS 154,272
- On the correlation between Hot Jupiters and stellar clustering: high-eccentricity migration induced by stellar flybys. Rodet, L. et al 2021. ApJ 913,104
- Accretion of substellar companions as the origin of chemical abundance inhomogeneities in globular clusters. Winter, A., Clarke, C., 2023. MNRAS 521,1646

Project 38: FU Orionis stars and other high-amplitude (slow) variables

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Supervisor III: Miguel Vioque (miguel.vioque@alma.cl)

UTO: Cathie Clarke (cclarke@ast.cam.ac.uk)

Project Summary

You will compare 2 optical surveys separated in time by over 50 years to search for high amplitude variables across the whole sky. The first survey is represented by a single catalogue: USNO-B which was compiled in 2003 (Monet+2003) from photographic plates taken between 1949 and 2002, and contains over 1 billion objects with multi-epoch, multi-colour photometry (and astrometry). The most recent survey is the Gaia all-sky survey, as published in Data Release 3 in June 2022, and containing 1.8 billion sources (Brown+23). The primary focus will be to discover large outbursts from pre-main-sequence stars (also known as Young Stellar Objects, or YSOs), specifically you will be searching for FU Orionis events, where a YSO brightens by a factor ~100 for decades (maybe even up to 100 years).

This project aims to discover larger samples of YSO events than found by previous studies (e.g., Contreras Peñas+19, Scholz+13). Statistically robust measurement of the number of FU Ori events will give improved insights into their occurrence rate. To try to learn more about the underlying physics driving these events, you will investigate any correlations between the properties of the star and the nature of the outburst (e.g., evolutionary-stage, stellar mass, brightness amplitude, duration of rise).

Questions to consider could include:

(i) do all stars go through 1 or more FUOR phases?
(ii) How much does the accretion rate change by?
(iii) What might be the impacts on planet formation (e.g., the meter barrier problem: Hubbard+17, Boley+14)?

To achieve these goals, you will follow a data-driven approach which will enable you to find events associated with previously unclassified YSOs. You will also use larger and improved catalogues of YSOs (and other classes of source) published in the last 3-4 years to aid with their classification (as well as identification of contaminants).

Background

Some of the rarest and most dramatic astrophysical outbursts are hard to catch 'in-the-act'. FU Orionis events (aka FUORs) in particular are slow moving, and involve the brightening of a pre-main-sequence star, taking over a year (or more) to reach maximum brightness, and lasting for at least decades. This brightening has been attributed to a high-accretion, high-luminosity phase in the proto-stellar disk.

FUORs are not the only events we will expect to see. Other high amplitude events could be caused by:

1. Lower amplitude erratic variability from other classes of YSO.

2. Symbiotic stars: consisting of a giant star and an accreting white dwarf.
3. High amplitude events from Cataclysmic Variables and accreting Black-hole binaries (XRBs),
4. High-amplitude extragalactic events such as AGN, Supernovae, Changing-Look QSOs, and Tidal Disruption Flares.

It will be important to identify which of the discovered events can be reliably associated with young stars by a variety of methods (location in 3D space, optical-infrared photometry, kinematics). You will also assess the evolutionary status of the candidate YSOs (i.e., the contribution of the disk to the luminosity of the systems in the infrared). You will need to compare your findings and methods with previous studies (e.g., Contreras Peña+19 and Scholz+13).

You will need to pay special attention to interspersed photometric measurements which may be extracted from publicly accessible optical and infrared surveys such as SDSS, Gaia DR1, Gaia DR2, PanSTARRS1, PTF, ZTF, ASAS, and WISE.

The other classes of event which you will undoubtedly discover are also interesting and have value. For example, large amplitude Changing-Look QSOs may look quite similar, and may have connected physics. The breakdown of the different classes of events that you discover by number, brightness, colour, and amplitude will be particularly important for the preparation of upcoming transient/time-domain surveys such as LSST.

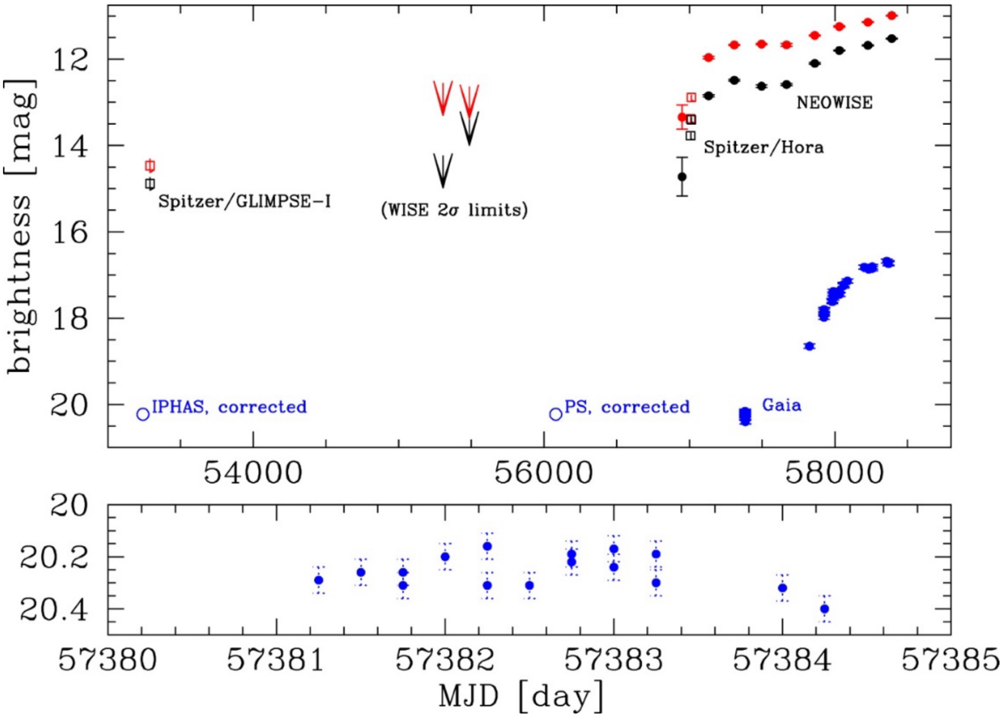

Figure 1.: Caption Figure and caption from Hillenbdrand+2018. Top: light curves measured by Gaia (G band with an effective wavelength 0.673 µm) in blue filled symbols and NEOWISE (3.4 and 4.6 µm) in black and red filled symbols. The recent photometry measuring the outburst is supplemented by previous data (open symbols) from the IPHaS and PanSTARRS surveys in the optical, corrected from r band to G band as described in the text, and from Spitzer in the infrared, plotted as the native 3.6 and 4.5 µm measurements, without correction. Error bars are shown on all points. Downward pointing arrows indicate the epochs of position coverage by the WISE sky survey, in which the source was not detected. Bottom: zoomed-in to the first epochs of Gaia data, taken in the last days of 2015. Notional 5% uncertainties are plotted as dotted error bars, derived by inflating the GaiaDR2 uncertainty for the number of transits included in the scatter measurement. If the real uncertainties are at this level or smaller, variability at the several tenths of a magnitude level could have been occurring before the major brightening episode.

Project Details

You will use the Cambridge Whole-Sky Database to compare the two surveys (USNO-B and Gaia DR3) and look for sources which have brightened (or faded) significantly over the intervening years. This will use a positional crossmatch, and make use of the Gaia measured proper motions to predict the source positions in the previous photographic survey. All candidates will need validation that the event is real (and not just a catalogue or matching problem). The next step will involve classification of the sources of the events using near-infrared and mid-infrared survey data from surveys such as 2MASS, UKIDSS, WISE and the VISTA Hemisphere Survey. Catalogues of classified objects will be used to build training sets (or to give direct classification), and UV and X-ray data will also be useful, particularly for classifying AGN, QSOs, CVs and XRBs. Note that candidates which are bright enough in Gaia DR3 will also have low dispersion XP spectroscopy, which may prove very helpful for their classification.

Skills Required

- You will use simple queries in PostgreSQL to build up samples of candidate large amplitude variables. Some known examples will be found in the literature and used to guide your search.
- Programming in python is preferred, but other languages can be supported.
- Machine Learning approaches may be justified for classification of your candidates - but is not required.

Useful References (List of important papers/review articles relevant to the project)

- https://ui.adsabs.harvard.edu/abs/2013MNRAS.430.2910S/abstract: Scholz et al. 2013, A systematic survey for eruptive young stellar objects using mid-infrared photometry:
- https://ui.adsabs.harvard.edu/abs/2018ApJ...869..146H/abstract: Hillenbrand et al. 2018, Gaia 17bpi: An FU Ori-type Outburst
- https://ui.adsabs.harvard.edu/abs/2019MNRAS.486.4590C/abstract: Contreras Peña et al. 2019, Determining the recurrence time-scale of long-lasting YSO outbursts
- https://ui.adsabs.harvard.edu/abs/2020A%26A...644A..49M/abstract: Merc et al. 20202, Gaia18aen: First symbiotic star discovered by Gaia

General References (List of papers referred to in the project)

- https://ui.adsabs.harvard.edu/abs/2003AJ....125..984M/abstract Monet et al. 2013, The USNO-B Catalog
- https://www.aanda.org/articles/aa/full_html/2023/06/aa43940-22/aa43940-22.html: Vallenari et al. 2023, Gaia Data Release 3

Project 39: Using Gaia BP/RP spectra to estimate astrophysical parameters

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Supervisor II: Giorgia Busso (giorgia@ast.cam.ac.uk)

UTO: Vasily Belokurov (vasily@ast.cam.ac.uk)

Project Summary

The project aim is to generate synthetic photometry in several photometric systems using the Gaia DR3 low-resolution spectra, to explore the performances of different combinations to estimate metallicities and other parameters such as alpha abundance, and to use external catalogues of astrophysical parameters for a subset of the sources in Gaia DR3 to calibrate a relation between the synthetic photometry and the parameter of interest that can be applied to a variety of objects.

Background

One of the new data products included in Gaia Data Release 3 (Gaia DR3, Vallenari et al. 2023) is an all-sky catalogue low-resolution spectra: 220 million objects, covering the entire sky, mostly brighter than G = 17.65, were observed with the Blue and Red Photomer (BP and RP respectively) in the wavelength range 330-1050 nm. Their processing is described in De Angeli et al. 2023 and Montegriffo et al. 2023B.

The BP and RP spectra in Gaia DR3 have already been used to determine astrophysical parameters such as metallicity, gravity and extinction adopting several techniques (Creevey et al. 2023, Fousneau et al. 2023, Andrae et al. 2023). The next Gaia data release (Gaia DR4, scheduled to take place not before the end of 2025) will vastly increase the number of published spectra up to the size of the astrometric and photometric Gaia catalogue (1.7 billion objects), offering the possibility of exploring different populations in our Galaxy. The entire catalogue of BP/RP spectra in Gaia DR4 will have a size of several tens of TB. The Gaia Data Analysis Consortium (DPAC) is planning to generate and publish synthetic photometry in a set of passbands, still to be defined. This would constitute a more manageable dataset which might allow an initial investigation / selection of interesting objects to be analysed further by extracting the corresponding full spectra. The results of this project might influence the choice of the passbands for which synthetic photometry will be added to Gaia DR4.

Synthetic photometry in a given photometric system, defined as a set of passbands, can be generated for the entire Gaia DR3 BP/RP spectra catalogue by convolving the spectra with the transmission curves of the various filters, with the constraint that the passbands need to be within the wavelength range covered by the BP/RP instruments and have a characteristic width is larger than the effective line spread function (LSF) of the spectra at the relevant wavelength (Montegriffo et al. 2023A). Fig. 1 shows an example of the Gaia BP/RP passbands compared with those in the Johnson (UBVRI) and SDSS (ugriz) photometric systems. Synthetic photometry in various systems can then be generated efficiently from the published spectra using the Python package GaiaXPy (https://gaia-dpci.github.io/GaiaXPy-website/).

Synthetic photometry in selected systems can be a very powerful resource when estimating astrophysical parameters in general and metallicity in particular. This can be useful for a first exploration, which can then be refined with more advanced techniques.

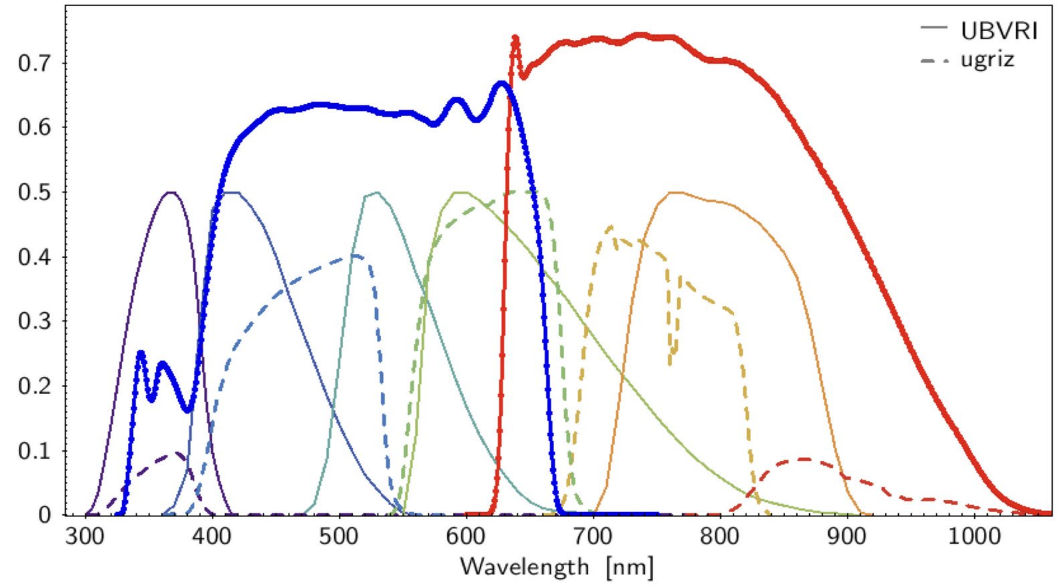

Figure 1.: Gaia BP/RP passbands compared with the Johnson (UBVRI) and SDSS (ugriz) photometric systems.

Project Details

The project entails extracting low-resolution spectra from the Gaia archive and familiarise with their properties. The spectra will then be used to generate the synthetic photometry with GaiaXPy with the aim of comparing the performances of different (even newly defined) photometric systems and different combinations of filters (colours) in estimating astrophysical parameters. Relationships to convert synthetic colours into the desired parameter measurement will need to be calibrated relying on available external catalogues from higher resolution instruments (e.g., GALAH, Buder et al. 2021, or APOGEE, Ahumada et al. 2020). It is likely that the calibration will need to take into account other properties of the objects under study, or depend on other astrophysical parameters. See also Bellazzini et al. (2023) and Martino et al. (2023) for a similar application.

Skills Required

- This project requires some programming/scripting ability (preferably in Python) and familiarity with basic statistical analysis techniques.
- There will be a degree of background reading to familiarise with the Gaia Mission and the characteristics of photometric systems, assessing similar previous analysis and the suitability of existing external catalogues.
- No specific lecture courses required though some background knowledge of stellar evolution and properties (e.g., Part II Astrophysics Structure and Evolution of Stars) would be advantageous.

General References (List of papers referred to in the project)

- Standard Photometric Systems, Bessel 2005, ARA&A, 43, 293B

- Gaia Data Release 3: Summary of the contents and survey properties, Gaia Collaboration, Vallenari, A., et al., A&A 674, A1 (2023)
- Gaia Data Release 3: Processing and validation of BP/RP low-resolution spectral data, Gaia Collaboration, De Angeli et al., A&A 674, A2 (2023)
- Gaia Data Release 3: The Galaxy in your preferred colours: Synthetic photometry from *Gaia* low-resolution spectra, Gaia Collaboration, Montegriffo et al., A&A 674, A3 (2023)-A
- Gaia Data Release 3: External Calibration of BP/RP low-resolution spectral data, Gaia Collaboration, Montegriffo et al., A&A 674, A3 (2023)-B
- The GALAH+ survey: Third data release, Buder et al. 2021, MNRAS, 506, 150
- The 16th Data Release of the Sloan Digital Sky Surveys: First Release from the APOGEE-2 Southern Survey and Full Release of eBOSS Spectra, Ahumada et al. 2020, ApJs, 203, 21
- Photometric metallicity for 694 233 Galactic giant stars from Gaia DR3 synthetic Strömgren photometry, Bellazzini et al., A&A 674, A194 (2023)
- The Pristine survey -- XXIII. Data Release 1 and an all-sky metallicity catalogue based on Gaia DR3 BP/RP spectro-photometry, Martin et al., arXiv:2308.01344

Project 40: Hidden Cooling Flows in Elliptical Galaxies

Supervisor I: Andrew Fabian

Supervisor II: Jiachen Jiang

UTO: Vasily Belokurov

Project Summary

X-ray analysis of the spectra of the hot interstellar gas in 3 massive elliptical galaxies will be used to determine the level of absorption and mass cooling rate of the gas.

Background

Elliptical Galaxies are sometimes described as "red and dead", which means that they lack normal star formation of the type found in spiral galaxies like the Milky Way. They do however have significant atmospheres of hot X-ray emitting gas of which the inner dense parts can form a cooling flow in which the gas drops in temperature while flowing inward toward the nucleus. Energy and momentum feedback from a central active nucleus may prevent any large cooling flow forming. A residual inflow may nevertheless occur with a mass inflow rate of about one Solar mass per year in some massive galaxies. The fate of the cooled gas is unclear, but it may form cold gas clouds and low-mass stars, some of which accrete into the central massive black hole. The project aims to measure the inflow rate for 3 relatively nearby ellipticals using X-ray spectra obtained from the Reflection Grating Spectrometers on ESA's XMM X-ray Observatory. One of the galaxies is the jetted Radio Galaxy Fornax A.

The Project is an extension of a wider search for Hidden Cooling Flows in Groups and Clusters of galaxies, where the mass cooling rates can be tens to hundreds of Solar masses per year.

Project Details

Spectral analysis of the RGS data of 3 elliptical galaxies will enable the temperatures, metal abundance and mass cooling rate of the interstellar gas to be determined.

Absorption of the X-rays from the cooling gas by gas that cooled earlier may hide the full emission from direct view, complicating the measurement of the total mass inflow rate. An intrinsic absorption model in which emission and absorption are interleaved (Allen & Fabian 1997; Liu et al 2019) will be used to model absorption distributed throughout the emission region. Modifications to the absorption model will be investigated. The total column density of the cold absorbing gas will be determined. HST data will also be used to search for absorption in the optical band.

The final report will put the results in context including discussion and comparison of the properties of the target galaxies.

Skills Required

- Basic computing skills are required.
- Spectral fitting will use the XSPEC package for which basic training will be given.

Useful References (List of important papers/review articles relevant to the project)

- Fabian AC et al 2022, MNRAS, 515, 3336; Fabian AC et al 2023a, MNRAS, 521, 1794: Fabian et al 2023b, MNRAS 524, 716; Liu H et al 2019, MNRAS, 485, 1757

General References (List of papers referred to in the project)

- Allen SW Fabian AC 1997, MNRAS, 286, 583; Fabian AC 1994, ARA&A, 32, 277; Fabian AC 2012, ARA&A, 50, 455A

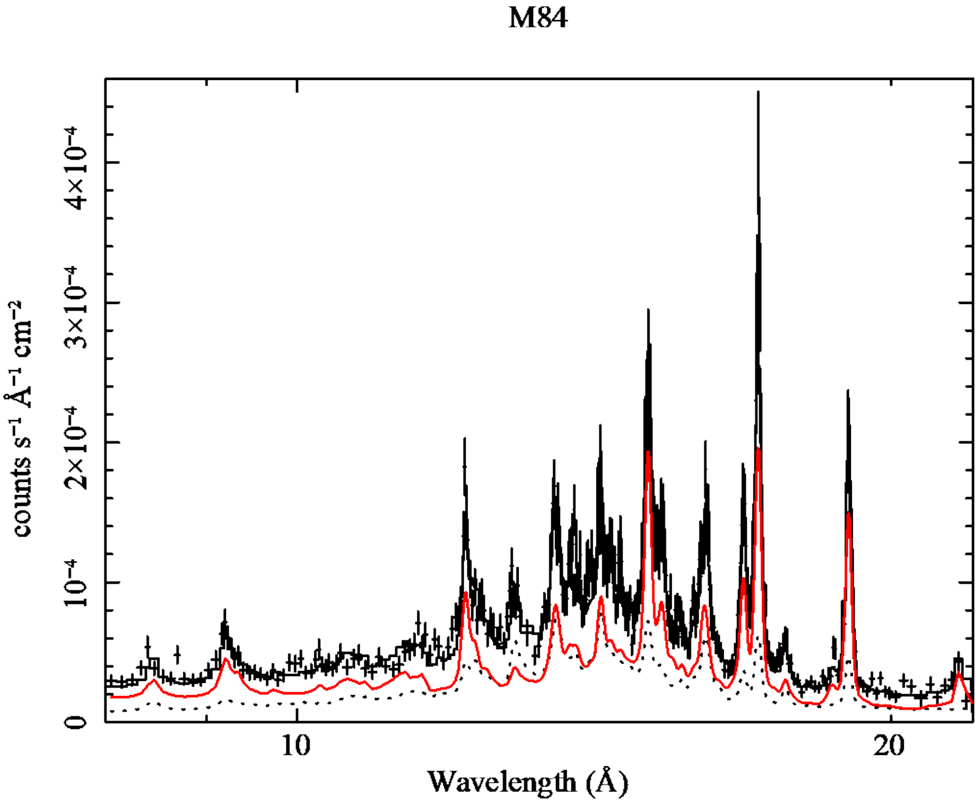

Figure 1.: Example RGS X-ray spectrum of the elliptical galaxy M84. The data are the black points, and the cooling flow component is shown in red. The dashed line shows the level of emission from the outer gas which is at a constant temperature.

Project 41: Hunting for Supermassive Black Hole binaries with Gaia

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Supervisor III: Simon Hodgkin (sth@ast.cam.ac.uk)

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Project Summary

This is a data mining project focused on discovery of a rare type of objects - close pairs of quasars.

Background

Most galaxies host a supermassive Black Hole (SMBH, e.g., Kormendy & Ho 2013). How and when such SMBHs were seeded is a cutting-edge question (Volonteri 2010). The subsequent growth of SMBHs is also an open question (Yu & Tremaine 2002). When their host galaxies merge, the SMBHs should, in principle, also merge, forming first a binary SMBH system and eventually fusing together into a single BH (see e.g., Begelman et al 1980, Merritt & Milosavljević 2005). In the future, with e.g., LISA, these mergers will be observable through the accompanying gravitational wave emission (see Jaffe & Backer 2003, Wyithe & Loeb 2003), however, currently these close SMBH binaries are too difficult to “see”, yielding only a handful of discoveries (see e.g., Komossa et al 2003). The details of the merger process of these SMBHs are unknown. This project will test and improve upon a novel technique of identifying close pairs of SMBH whilst they are still in their active quasar phase. The method relies on detecting small shifts of the observed photo-centre of two QSOs using astrometric data from the Gaia satellite, using a technique known as varstrometry (see Hwang et al 2020).

If the binary QSO is unresolved by Gaia, i.e., it appears as a single object, the centroid of the light from two individual sources will move about if the flux contribution from one or both sources is changing with time. Most QSOs are indeed variable sources (see e.g., Hook et al 1994), making the hunt for the unresolved binary QSO pairs promising. This project will build on the ideas developed in the published varstrometry papers (e.g., Hwang et al 2020) and will improve the selection of promising binary QSO candidates by:

i) using the new Gaia DR3 data (Hwang et al 2020 used Gaia DR2) and

ii) using new, larger catalogues of QSOs (e.g., that by Storey-Fisher et al 2023).

In the hunt for binary QSOs, multiple false positives are expected (see Hwang et al 2020). Binary stars and stellar blends can produce the expected astrometric “jitter” signal and is a particular problem for stars with spectral energy distributions similar to the QSO’s, i.e., White Dwarfs and Cool low-mass dwarfs. Additionally, many galaxies have a sharp central stellar density enhancement or sometimes a star cluster that can appear as a point source to Gaia. In this case, any additional morphological complication (extended shape, irregular shape, dust, multiple star-forming regions) can mimic binary QSO signal. This is exacerbated by the fact that Gaia’s astrometric measurements for the majority of the sources are 1-dimensional. The orientation of these 1-dimensional scans changes with time as the

Gaia's view of the sky rotates thus producing a series of slices through a non-circularly symmetric image, resulting in the shift of the centroid. In the case of active galactic nuclei, jets (or bright spots on their ends) can provide a source of optical variability and astrometric jitter. Finally, gravitationally lensed QSOs would be almost indistinguishable from binary QSO pairs. The only difference is that each of the sources contributing to the light centroid will have the same light-curve, offset in time by the delay associated with its particular travel time in the lens. The nature of the varstrometry candidates selected with Gaia DR2 has been investigated using HST high-resolution imaging and is discussed in Chen et al 2022 - we show some of the interesting objects from that sample in Figure 1.

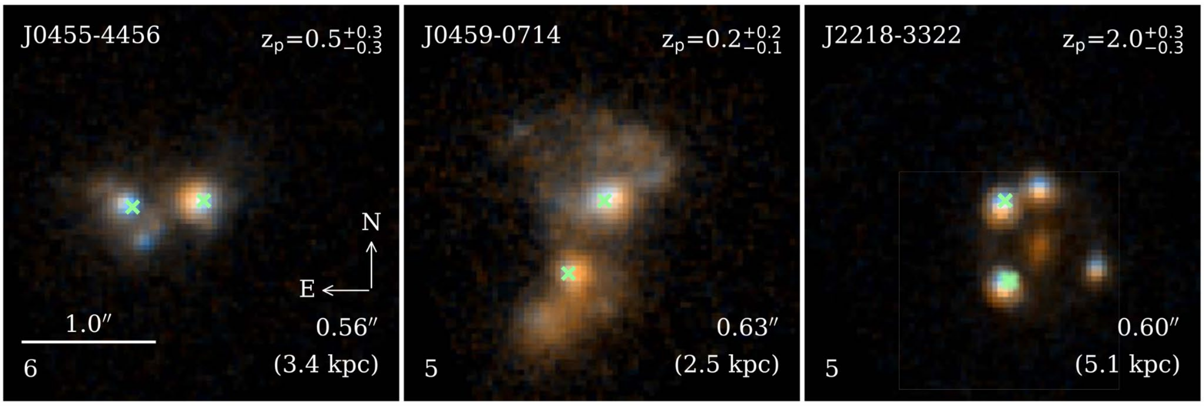

Figure 1.HST/WFC3 colour composite images of three highlighted targets. Left: a triple quasar candidate with an irregular tidal feature. Middle: a dual quasar candidate with an irregular tidal feature. Right: a quadruply lensed quasar. This is a reproduction of Figure 8 from Chen et al 2022

Project Details

First, the student will use Gaia DR3 data to investigate the published QSO pair candidates selected using the varstrometry method with the Gaia DR2 data. This will help to verify the validity of the method and identify the most common false positives. The student can also test how the amount of astrometric jitter depends on the shapes of Galactic nuclei (using imaging from surveys like PS1 and DESI) and correlates with optical variability (using lightcurves provided by ZTF). If there is time, the student can come up with a new set of selection criteria to disentangle the candidate systems into various classes (see the list of false positives above) paying close attention to semi-resolved blends with angular separation of <1 arcsecond and genuine single sources.

There are at least two possible ways to collect the statistics of binary QSOs:

i) create a highly pure sample (at the expense of strong and complicated selection biases) and

ii) create a sample with imperfect purity but simple and well-understood selection effects. The student can investigate the merits of both approaches.

In the first case, if strong candidates for binary QSO are identified, a follow-up observing proposal can be written to clarify the nature of the best quality systems with adaptive optics instruments and/or HST/JWST. In the second case, the student will study the incidence of the binary QSOs as a function of redshift, luminosity etc.

Skills Required

- Some knowledge of galaxy formation and evolution would be useful.

- Part III lecture course “Life and Death of Galaxies”
- Most coding will be in Python. The project will make use of large databases so some SQL will be used too.

Useful References (List of important papers/review articles relevant to the project)

- Hwang et al 2020 https://ui.adsabs.harvard.edu/abs/2020ApJ...888...73H/abstract
- Chen et al 2022 https://ui.adsabs.harvard.edu/abs/2022ApJ...925..162C/abstract
- Storey-Fisher et al 2023 https://ui.adsabs.harvard.edu/abs/2023arXiv230617749S/abstract

General References (List of papers referred to in the project)

- Kormendy & Ho 2013 https://ui.adsabs.harvard.edu/abs/2013ARA%26A..51..511K/abstract
- Volonteri 2010 https://ui.adsabs.harvard.edu/abs/2010A%26ARv..18..279V/abstract
- Yu & Tremaine 2002 https://ui.adsabs.harvard.edu/abs/2002MNRAS.335..965Y/abstract
- Begelman et al 1980 https://ui.adsabs.harvard.edu/abs/1980Natur.287..307B/abstract
- Jaffe & Backer 2003 https://ui.adsabs.harvard.edu/abs/2003ApJ...583..616J/abstract
- Komossa et al 2003 https://ui.adsabs.harvard.edu/abs/2003ApJ...582L..15K/abstract
- Merritt & Milosavljević 2005 https://ui.adsabs.harvard.edu/abs/2005LRR.....8....8M/abstract
- Wyithe & Loeb 2003 https://ui.adsabs.harvard.edu/abs/2003ApJ...590..691W/abstract
- Hook et al 1994 https://ui.adsabs.harvard.edu/abs/1994MNRAS.268..305H/abstract

Project 42: Connecting the Milky Way's mass assembly history and its present-day satellite population properties with Geometric Deep Learning

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Supervisor II: Miles Cranmer (mc2473@cam.ac.uk)

UTO: Vasily Belokurov (vasily@ast.cam.ac.uk)

Project Summary

This project will train a graph neural network to predict the properties of the dwarf satellite population of a Milky Way-mass galaxy at redshift z=0 given the host's merger tree. The idea is to test the connection between the recently constrained Milky Way's assembly history and its observed dwarf satellites. In doing so, we will also explore new techniques in the space of interpretable machine learning.

Background

The Milky Way, as any galaxy of similar mass, is surrounded by >100 of low-mass dwarf satellites each inhabiting a small Dark Matter halo of their own (e.g., Simon 2019, Drlica-Wagner et al 2020). By modelling the properties of the present-day population of these dwarf satellites, one can place constraints on the poorly understood physics of the early structure formation (e.g., gas cooling, star formation in metal poor regime, re-ionisation) as well as the properties of the Dark Matter itself (e.g., Jethwa et al 2018, Nadler et al 2021, Manwadkar & Kravtsov 2022). The current models of the Galactic dwarf satellites use the so-called zoom-in approach where an approximately 1 Mpc-sized box is selected from a large low-resolution Cosmological simulation and then re-run with a higher resolution (e.g., Hahn & Abel 2011, Garrison-Kimmel et al 2019). Models of dwarf satellites rely on matching the observed Milky Way to its simulated zoom-in counterparts using the Virial, i.e., total, DM host mass at redshift z=0. Yet at fixed host mass, there exists a substantial scatter in the properties of the Dark Matter (e.g., concentration, triaxiality) and its sub-structure such as dwarf galaxies (their total number, spatial distribution etc). This scatter is controlled by the details of the host's mass assembly history. If the accretion histories can be sampled and the satellite population models can be conditioned on the observed host's accretion history, it is likely that the uncertainties can be shrunk. However currently available zoom-in suites are too small (typically containing only 20-40 simulated MWs) to provide a wide enough range of model accretion histories.

Most recently, thanks to the data from the Gaia satellite, we have started to obtain strong constraints on the mass assembly of our Galaxy. MW's life has been shown to be punctuated by three principal events: the Gaia Sausage/Enceladus merger (Belokurov et al 2018, Helmi et al 2018), the Sgr dwarf accretion, and the accretion of the Magellanic Clouds. Such accretion histories are not very common. Requiring a galaxy to have a similar accretion history (i.e., dominated by events with a mass ratio and a timing similar to that of the GS/E and the MCs) gives only 0.65% of all possible MW-mass systems (Evans et al 2020). Even just the late arrival of the LMC (with SMC) to the Galaxy is a pretty unusual event by itself (Boylan-Kolchin et al 2010, Liu et al 2011). There is a clear disconnect between the MW observations which have become more precise and the available simulations which appear to reproduce the MW (in particular, its mass assembly history) only approximately.

First attempts have already been made to demonstrate that a connection exists between the MW's assembly history and its global properties. For example, requiring an analogue of the GS/E event in the simulated galaxy's life results in a noticeably lower DM spin at redshift z=0 (Dillamore et al 2023a). MW analogues dominated by the GS/E mergers also appear to form a stellar disk earlier than same-mass hosts with extended accretion histories (see Dillamore et al 2023b, Semenov et al 2023). However, little has been done to understand the connection between the accretion history and the present-day dwarf satellite population, with the only published attempt by Bose et al (2020).

This Project will use geometric deep learning methods to learn to predict properties of the z=0 satellite population given a merger tree. More precisely, we will extend the Mangrove model (Jespersen et al 2022) which has been demonstrated to successfully predict broad-brush properties of galaxies: stellar mass, gas mass, black hole mass, metallicity, and star formation rate.

Mangrove is a type of graph neural network which works directly on the natural merger tree structure of a galaxy's accretion history, without needing to project the merger tree into a tabular, sequence, or grid-based representation. Individual merger events throughout the universe's history are represented as nodes in the graph and include information about resultant galaxy properties. Edges in the graph represent the passage of time from one merger event to the next (see Fig. 1). Thus, a single connected graph includes all merger events in a galaxy's history and is fed into the graph neural network for prediction.

In the original Mangrove paper, the model was trained on merger trees from a dark matter-only version of IllustrisTNG (TNG-100-1-Dark). As this simulation was generated using only dark matter, baryonic matter has been painted on via sophisticated post processing using the Santa Cruz Semi-Analytic Model (Somerville et al., 2015). This forms the training data for Mangrove. Thus, it may not accurately emulate all relevant dynamical processes that a zoom-in simulation would give us.

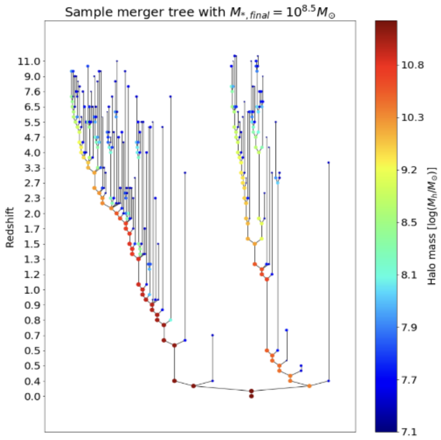

Figure 1. A graphical representation of a merger tree for an example galaxy's accretion history. Each node is a merger event, and each edge shows the passage of time between merger events. The root node at z=0 is the final galaxy whose properties we wish to predict.

Project Details

The student will re-train the Mangrove on a new set of merger trees as inputs and a set of satellite properties as outputs. Mangrove is available at https://github.com/astrockragh/Mangrove.

We will consider using several publicly available zoom-in simulation suites (and the associated merger trees and z=0 snapshots). For Dark Matter only (without gas dynamics and stars) we will use Caterpillar available at https://www.caterpillarproject.org and ELVIS. These simulations have high enough resolution to track DM sub-halos down to the masses corresponding to the faintest dwarf satellites of the MW. However these simulations do not model the effects of the baryons which may be important for the internal evolution of the most massive dwarfs (see e.g. Brooks et al 2014). The baryonic disk of the MW is also alleged to aid disruption of small satellites thus changing the z=0 population properties (see e.g., Garrison-Kimmel et al 2017). The effects of the baryons can possibly be modelled with semi-analytic prescriptions. Alternatively we can train the Mangrove on hydro-dynamical simulations which include the effects of baryons. Publicly available hydrodynamical simulations suites include Auriga (https://wwwmpa.mpa-garching.mpg.de/auriga/), FIRE (https://fire.northwestern.edu/data/) and ARTEMIS (Font et al 2020).

To train Mangrove we will need merger trees (assumed to be built and included with the simulations). The student will design the necessary outputs based on the properties of the dwarf satellites (or DM sub-halos of appropriate mass) surviving to be detected in the z=0 snapshot. Possible outputs may include: the total number of satellites, the mass/luminosity functions of satellites, concentration of the satellite radial distribution, “diskiness” (how planar the distribution is) of the satellite spatial distribution. GRUMPY code could be used to “paint” z=0 properties of the satellites onto the DM sub-halos, see https://github.com/kibokov/grumpy

Mangrove uses PyTorch (pytorch.org) and PyTorch Geometric (pytorch-geometric.readthedocs.io). It uses GraphSAGE (Hamilton et al 2017 & https://snap.stanford.edu/graphsage/) as its variant of a graph neural network. The student will become familiar with these frameworks, how to process and load data with them, and how to use them to train a neural network. Optionally the student can use PyTorch Lightning (lightning.ai) which automates aspects of training. We will need to design an objective that can be used for training the neural network to predict properties of the dwarf satellite position, and also need to create an analysis pipeline for visualising and verifying the predictions of the network.

Skills Required Coding in Python.

- Part III Lectures “Life and Death of Galaxies”

Useful References (List of important papers/review articles relevant to the project)

- Belokurov et al 2018 https://ui.adsabs.harvard.edu/abs/2018MNRAS.478..611B/abstractEvans et al 2020 https://ui.adsabs.harvard.edu/abs/2020MNRAS.497.4311E/abstract
- Boylan-Kolchin et al 2010 https://ui.adsabs.harvard.edu/abs/2010MNRAS.406..896B/abstract
- Dillamore et al 2023 https://ui.adsabs.harvard.edu/abs/2023MNRAS.519L..87D/abstract
- Bose et al 2020 https://ui.adsabs.harvard.edu/abs/2020MNRAS.495..743B/abstract
- Jespersen et al 2022 https://ui.adsabs.harvard.edu/abs/2022ApJ...941....7J/abstract
- Somerville et al 2015 https://ui.adsabs.harvard.edu/abs/2015MNRAS.453.4337S/abstract

- Hamilton et al 2017 https://cs.stanford.edu/people/jure/pubs/graphsage-nips17.pdf
- For general tips on training neural networks and the many potential pitfalls you will encounter: https://karpathy.github.io/2019/04/25/recipe/

General References (List of papers referred to in the project)

- Simon 2019 https://ui.adsabs.harvard.edu/abs/2019ARA%26A..57..375S/abstract
- Drlica-Wagner et al 2020 https://ui.adsabs.harvard.edu/abs/2020ApJ...893...47D/abstract
- Jethwa et al 2018 https://ui.adsabs.harvard.edu/abs/2018MNRAS.473.2060J/abstract
- Nadler et al 2021 https://ui.adsabs.harvard.edu/abs/2021PhRvL.126i1101N/abstract
- Manwadkar & Kravtsov 2022 https://ui.adsabs.harvard.edu/abs/2022MNRAS.516.3944M/abstract
- Hahn & Abel 2011 https://ui.adsabs.harvard.edu/abs/2011MNRAS.415.2101H/abstract
- Garrison-Kimmel et al 2019 https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.1380G/abstract
- Helmi et al 2018 https://ui.adsabs.harvard.edu/abs/2018Natur.563...85H/abstract
- Liu et al 2011 https://ui.adsabs.harvard.edu/abs/2011ApJ...733...62L/abstract
- Semenov et al 2023 https://ui.adsabs.harvard.edu/abs/2023arXiv230609398S/abstract
- Garrison-Kimmel et al 2017 https://ui.adsabs.harvard.edu/abs/2017MNRAS.471.1709G/abstract
- Brooks et al 2014 https://ui.adsabs.harvard.edu/abs/2014ApJ...786...87B/abstract
- Font et al 2020 https://ui.adsabs.harvard.edu/abs/2020MNRAS.498.1765F/abstract

Project 43: Using Machine Learning to Probe Theories of Chaos in Planetary Systems

Supervisor I: Miles Cranmer (mc2473@cam.ac.uk)

UTO: Miles Cranmer (mc2473@cam.ac.uk)

Project Summary

This project will use interpretable machine learning techniques to probe what a neural network has learned about planetary dynamics. First, we will measure if the latent parameters inside a previously trained neural network (Cranmer et al., 2021) are correlated with common metrics found in theories of planetary instability. We will then explore if, using symbolic regression and other techniques for machine learning interpretability, we are able to find new symbolic metrics for dynamical instability. We will then see if we can derive or explain those metrics – which were discovered by the neural network – from first principles.

Background

The long-term evolution of compact planetary systems is determined by chaotic instabilities, but developing a general predictive theory has been unsolved for 300 years. Pure analytical approaches to this problem have proven ineffective in general configurations, working only for extremely simple cases. However, recently, tabular machine learning approaches using a variety of chaos indicators (Tamayo et al., 2020), as well neural networks which learn their own chaos indicators from scratch from time series data (Cranmer et al., 2021) have been shown to be surprisingly effective at predicting long term behaviour. In doing so, these models avoid the need for numerical integration, allowing dynamical instability to be used as a signal for exoplanet constraints (Arevalo et al., 2022). However, these black-box models offer little insight into what theory they may have actually learned about chaotic dynamical systems.

A number of existing metrics have been proposed to predict instability based on closed-form expressions. A classic approach by Wisdom (1980) gave a condition for instability based on applying a notion of overlap of nonlinear resonances in the orbits of a system, which leads to chaotic behaviour. More recent approaches such as Hadden & Lithwick (2018) consider overlap of higher order resonances. Petit et al., (2020) uses similar approaches to develop an analytic model to coarsely estimate the instability time of a planetary system with several simplifying assumptions. However, a general predictive theory remains elusive.

That being said, the neural network approach in Cranmer et al., 2021 (also see fig. 1 below), trained on about 10,000 numerical simulations, appears to outperform all existing theory. Why is this? What has this neural network learned? We can approach this with “symbolic regression” and a technique referred to as “symbolic distillation,” (Cranmer et al., 2020; Cranmer 2023). Symbolic regression is an interpretable machine learning task that finds analytic expressions to approximate a dataset. We can use this to find analytic approximations of parts of the neural network. This project will apply symbolic regression methods like PySR to neural networks trained on planetary dynamics, in hopes of extracting stability metrics that capture the models’ learned knowledge.

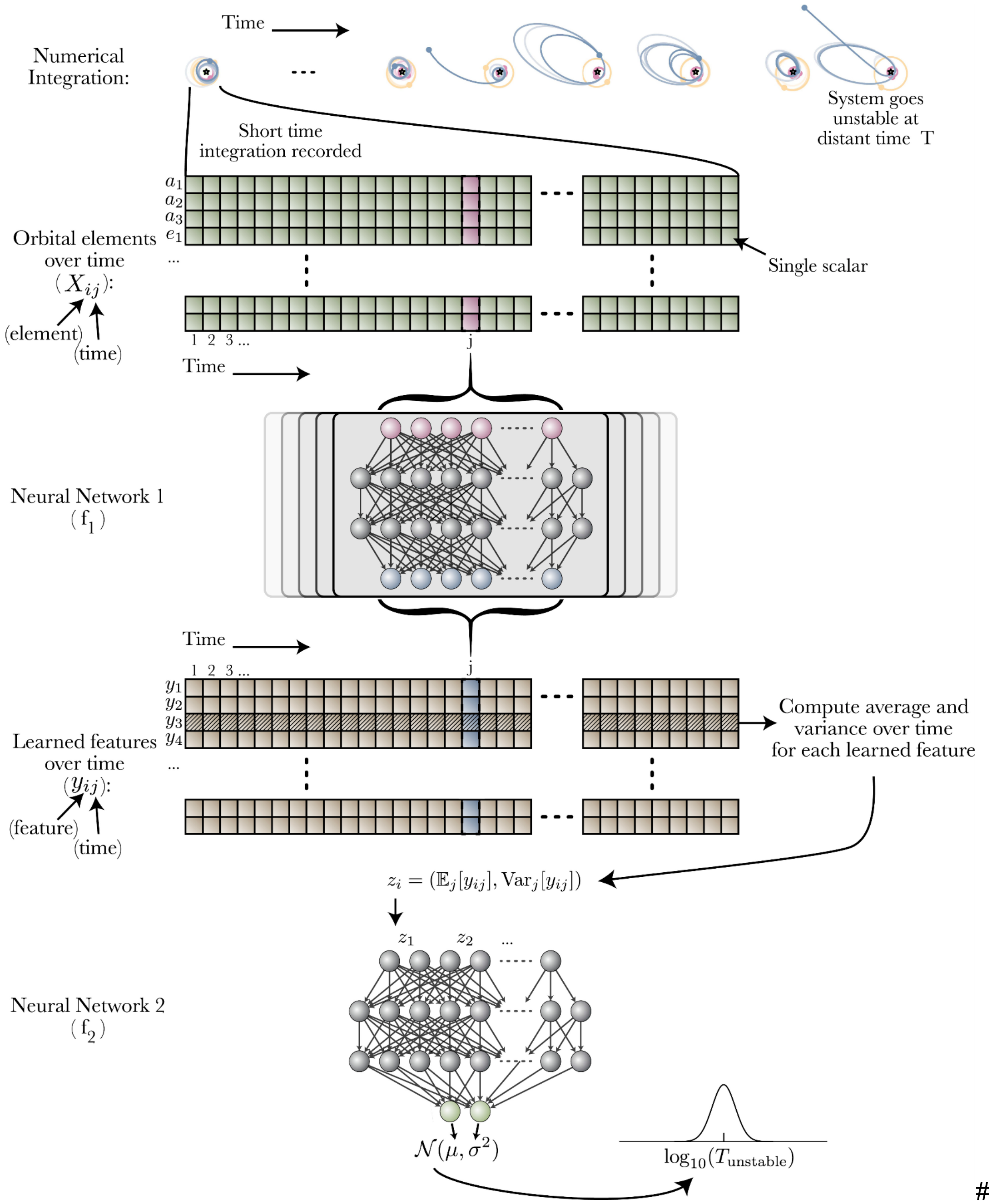

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Figure 1.: A diagram of the architecture of the model. Using a short integration of a planetary system (10k orbits), the model predicts at what time the system goes unstable.

Project Details

The student will download the model and code from https://github.com/MilesCranmer/bnn_chaos_model as well as the easier to use API from https://github.com/dtamayo/spock. Using these codebases, the student will first get comfortable in predicting instability time for different N-body planetary systems, verifying the results match up with rebound integrations (https://github.com/hannorein/rebound). Next, the student will record the inputs and outputs of the neural network latent spaces when making predictions for these systems. The student will write or download code that estimates traditional stability metrics, and explore whether there are any correlations between what the network has learned and theory-based metrics, which can help inform us what the neural network has learned.

Following this, the student will learn to use the PySR software (https://github.com/MilesCranmer/PySR) and apply it to find analytic approximations of the neural network latent spaces. Using what they have learned about the theory of planetary stability, we will consider whether these analytic expressions are similar to any existing theories, and whether there is any path to derive these expressions from first principles.

If time permits, we can look at training the model further with an expanded dataset, to obtain better metrics.

Skills Required

- Coding in Python
- Part III lectures "planetary system dynamics"
- Some prior knowledge of machine learning will be helpful

Useful References (List of important papers/review articles relevant to the project)

- Wisdom 1980 https://ui.adsabs.harvard.edu/abs/1980AJ.....85.1122W/abstract
- Hadden & Lithwick 2018 https://ui.adsabs.harvard.edu/abs/2018AJ....156...95H/abstract
- Petit et al., 2020 https://www.aanda.org/articles/aa/abs/2020/09/aa38764-20/aa38764-20.html
- Tamayo et al., 2020 https://www.pnas.org/doi/abs/10.1073/pnas.2001258117
- Cranmer et al., 2021 https://www.pnas.org/doi/abs/10.1073/pnas.2026053118
- Tamayo et al., 2021 https://iopscience.iop.org/article/10.3847/1538-3881/ac1c6a/pdf
- Cranmer et al., 2020 https://proceedings.neurips.cc/paper/2020/hash/c9f2f917078bd2db12f23c3b413d9cba-Abstract.html
- Cranmer 2023 https://arxiv.org/abs/2305.01582
- Arevalo et al., 2022 https://iopscience.iop.org/article/10.3847/2041-8213/ac70e0/meta

Project 44: Probing the [OIII] Planetary Nebulae Luminosity Function with Gaia

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Supervisor II: Vasily Belokurov (vasily@ast.cam.ac.uk)

UTO: Vasily Belokurov (vasily@ast.cam.ac.uk)

Project Summary

This project aims to better characterise a sample of Planetary Nebulae (PN) taken from a set with improved distances, as observed with the ESA Gaia satellite. The project will focus on determining the PN luminosity function (PNLF) for the set of Gaia selected Galactic PN and comparing this with the PNLF found from PN in nearby Local Group Galaxies.

Background

Planetary Nebulae are a brief evolutionary stage through which low and intermediate mass stars pass towards the end of their evolution, between red giant and white dwarf. They play an important role in the processing of a number of elements into the surrounding interstellar medium. They act as useful probes of kinematical structure of the Milky Way and provide insights into the chemical evolution history of the Galaxy. Understanding the global role of PN is limited due to large uncertainties in individual distances and to a detailed knowledge of the dynamics of their nebulae. These factors in turn constrain the absolute parameters of PN, such as their sizes, luminosities, masses, lifetimes and determination of the overall Galactic PN population.

The ESA Gaia satellite was launched in December 2013. Over the 5 years of its nominal mission, and now into its extended mission phase, it is mapping the positions, motions, and parallaxes (hence distances) to over a billion stars in the Milky Way. It is sensitive to objects to a limiting Gaia magnitude of G=20.7, achieving parallax errors of a few tens of microarcsecs for G=15 Solar type stars. The third major Gaia Data Release (Gaia EDR3: Dec 2020 and Gaia DR3 Jun 2022) provide parallax information for ~1.4 billion objects brighter than G~20.7.

Gaia is optimised for the detection of point sources, and in general is not sensitive to extended objects (with sizes ≥0.5 arcsec). However, Gaia is able to resolve structure within extended objects. This is demonstrated by commissioning observations of the large PN NGC 6543, where the complex nebula is decomposed by Gaia into thousands of individual mapping points.

This project will investigate the sample of Milky Way PN central stars that we (Chornay & Walton, 2020 and 2021) have matched to Gaia sources. The sample includes several hundred PN with confident matches and several hundred with probable matches. Fig 1 shows the location of these PN. For the PN matched to Gaia sources, improved distances will result.

The [OIII] PN luminosity function (PNLF) shows a well-defined shape and cut-off at the bright end, largely invariant across stellar populations in the disks and bulges of spiral galaxies, and also in elliptical and dwarf irregular galaxies. As such, the PNLF is an important rung of the extragalactic distance ladder, having been used to determine the distance of galaxies as far as Hydra at~50 Mpc (e.g. Ciardullo, 2012). It is still not clear as to why PN are such a reliable distance indicator across all galaxy types, as the brightest PN are thought to require higher-mass progenitors that should be absent from older stellar populations. Studies of the PNLF have been hampered by the difficulty in determining distances to Galactic PN. Now, with the improved Gaia selected PN catalogue, and new flux-calibrated narrowband [OIII] imagery from a recent observational campaign, it will be possible to accurately determine the PNLF for hundreds of PN within 3kpc of the Sun. The Gaia PN sample is large enough to enable the PNLF to be constructed for different regions of the Galaxy (e.g., Bulge cf outer Galactic Plane)

The faint end of the PNLF will be investigated as this probes the multiple populations of different ages that have formed the Galaxy, as for the case of M31 (Bhattacharya et al, 2021). Our Gaia selected PN will probe the PNLF to sufficiently low luminosities to investigate and unravel the effect of differing age populations, potentially probing accretion events such as Gaia-Enceladus (Belokurov et al, 2018).

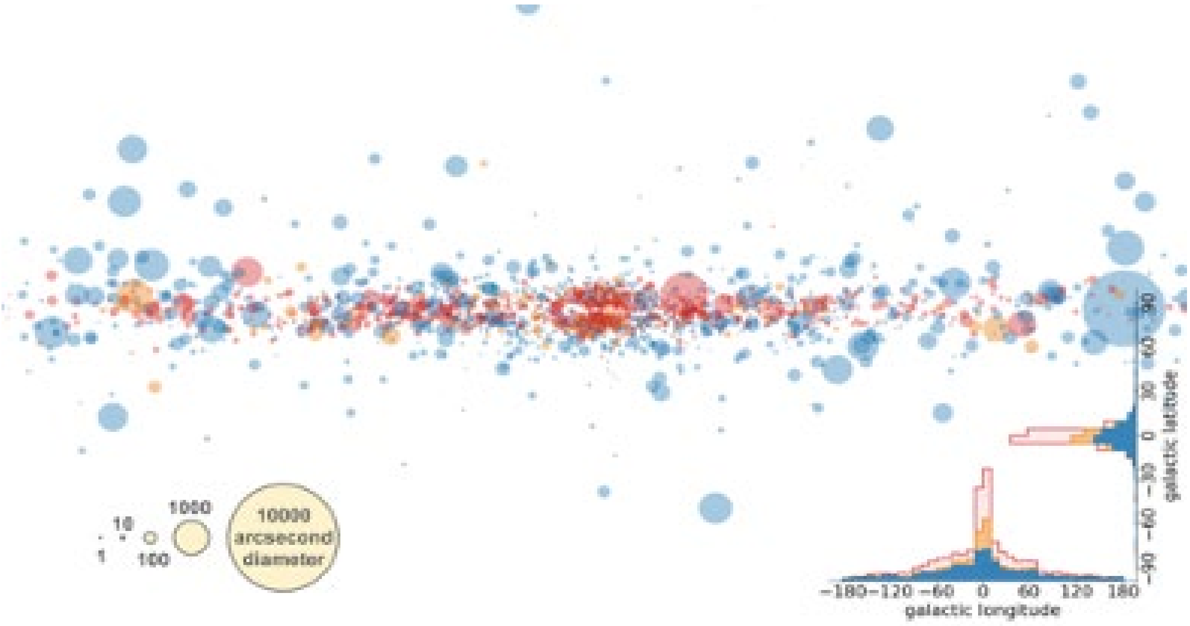

Figure 1: The image shows the location of known Galactic Planetary Nebulae. Blue: the PN is matched to a Gaia source; orange: possible match to a Gaia source: and red: no match to a Gaia source. The size of the circle gives an indication of the diameter of the nebula. Image credit: Nick Chornay}

Project Description

1. From the catalogue of PN with central stars observed by Gaia in Gaia (E)DR3, gather physical properties of the PN with good Gaia matches. This will involve collating a range of basic data about each PN, including sizes and fluxes.

2. Generate distance estimates for these PN, based on the Gaia parallaxes. This will include an estimation of the error on those distance measurements. Update physical parameters, such as absolute luminosity, based on the revised distances. Locate the PN central stars on the Hertzsprung-Russell diagram.

3. Type the PN into categories, for instance those being ’Type 1’ (derived from chemical abundances in the nebulae) and investigate potential clustering of these in the H-R diagram.

4. Determine the [OIII] fluxes for the Gaia selected PN, using data from previous surveys, or new data recently collected from our observational campaigns with the Isaac Newton 2.5-m telescope. Investigate use of the Gaia BP/RP to determine the [OIII] flux from the Gaia spectrophotometry alone.

5. Generate the [OIII] PN Luminosity Function for the Gaia selected PN, globally and for various sub samples. Further investigation will focus on the faint end of the PNLF.

The project will involve extensive use of ESA Gaia data (http://gea.esac.esa.int/archive/). Gaia EDR3 and DR3 will be used during the project. New (reduced) [OIII] imaging data will also be available.

Skills Required

- Ability to code in python will be an advantage, although not essential. Knowledge of MS Excel (or similar) will also be useful.
- The Part III/MASt course in "The Structure and Evolution of Stars" is relevant to this project.

Useful References (List of important papers/review articles relevant to the project)

- An example of early observations of the Cat's Eye PN by Gaia can be found at http://www.cosmos. esa.int/web/gaia/iow_20141205
- Gaia Data Release 3: Gaia Collaboration, Vallenari et al, 2023, A&A, 674, 1
- The Planetary Nebula Luminosity Function at the dawn of Gaia: Ciardullo, 2012, Ap&SS, 341, 151
- Searching for central stars of planetary nebulae in Gaia DR2, Chornay & Walton, 2020, A&A 638, 103
- One star, two star, red star, blue star: an updated planetary nebula central star distance catalogue from Gaia EDR3, Chornay & Walton, 2021, A&A, 656, 110
- Co-formation of the disc and the stellar halo, Belokurov et al, 2018, MNRAS, 478, 611
- Gaia Data Release 3. The Galaxy in your preferred colours: Synthetic photometry from Gaia low-resolution spectra: Gaia Collaboration, Montegriffo et al, 2023, A&A, 674, 33