Introduction

This booklet contains descriptions of the individual projects available in the academic year 2019/2020. Each entry contains a brief description of the background to the project along with a summary of the type of work involved and several references where more information can be obtained. The booklet is made available just before the start of the Michaelmas term to give students about 2 weeks to choose which projects they are interested in.

Vasily Belokurov  Part III/MASt Astrophysics Course Coordinator, Michaelmas term 2019
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**APPENDIX**

- Project timetable format and Content
- Criteria for Marking Project Report – oral and written
- Contact List for supervisors

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1. Radio Properties of Strongly Lensed Quasars

**Supervisors:** Matt Auger, K20, mauger@ast.cam.ac.uk; Richard McMahon, rgm@ast.cam.ac.uk

**UTO:** Richard McMahon

**Background:** Strong gravitational lensing produces multiple images of high-redshift systems, allowing the total mass of the foreground lensing objects (typically massive galaxies or clusters) to be precisely inferred whilst also magnifying the background objects (typically quasars or star-forming galaxies) thereby enabling them to be studied in greater detail (see Figure). The number of gravitationally lensed quasars has grown dramatically over the past two years, largely due to the Gaia and WISE missions, and nearly 300 systems are now known. Because QSOs are intrinsically very small, they are sensitive to mass distributions that themselves are also very compact, including dark matter substructures. These low-mass dark matter clumps lead to flux ratio anomalies in the lensed quasar images, i.e., deviations in the lensing amplification compared to what would result from a smooth mass distribution. The optical light of a lensed quasar is similarly affected by microlensing from stars in the lensing galaxy, but radio emission from quasars is extended over significantly larger – though still quite small – scales, such that any anomalous magnification must result from (presumably low-mass) dark matter structures. A census of radio emission in lensed quasars therefore provides a means of quantifying the amount of low-mass dark structure and, consequently, can rule out models for dark matter particles that produce too much or too little structure.

**This Project:** The Very Large Array (VLA) Sky Survey is a radio survey that has now observed the entire sky above a declination of -40 degrees, covering more than 90% of known quasar lenses. The highly motivated Part III student will cross reference a list of known lensed quasars with the survey data to quantify the radio fluxes of the lenses and compare with their optical properties. Flux ratios will be determined for the images of wider-separation lenses, and these will be used to constrain mass models for the lenses. A comparison with FIRST and NVSS data will be made to determine which lenses have significant radio variability, and a similar investigation will be made of lens candidates to aid in the discovery of new lenses. This project is heavily data oriented and a successful completion will require writing Python codes to manipulate and interpret catalogues and pixel-based data.

**Recommended Reading:**
  The first discussion of using strong lens flux ratios to constrain dark matter substructure.
  An investigation of dark matter structure for a sample of radio-loud lensed quasars.
  46 new quasar lenses discovered by our team at the IoA (another 49 will soon be published).
- https://public.nrao.edu/vlass/
- https://science.nrao.edu/science/surveys/vlass
  Resources describing VLASS, including its science goals and observing strategy.
(Left) Hubble Space Telescope multi-colour image of the lensed quasar RXJ1131-1231, showing the lensing galaxy, the four lensed quasar images, and the quasar host galaxy lensed into several Einstein arcs and rings. (Right) VLA 5 GHz image of the same lens, showing radio counterparts to the optical quasars. In this lens, the foreground lensing galaxy is also a radio source. The VLASS data at ~3 GHz have lower resolution and sensitivity but the lensed emission is still detected.
2. OSARGs – new standard candle for the Galaxy

Supervisor I: Vasily Belokurov, H20, Vasily@ast.cam.ac.uk  
Supervisor II: Sergey Koposov, skoposov@cmu.edu  
UTO: Vasily Belokurov

Project summary:

This Project looks to create a large sample of stars with accurate distances across the entire Milky Way irrespective of the metallicity or age. This will be achieved using OGLE Small Amplitude Red Giant stars (OSARGs). There exist two main complications to using OSARGs as standard candles: i) they are quasi-periodic, meaning that their Fourier spectra are multi-harmonic and ii) they exhibit several Period-Luminosity relations (rather than one). However, as has been demonstrated recently, these issues can be successfully circumnavigated. As Rau et al (2019) demonstrate using a combination of light-curve shape features and an algorithm based on Machine Learning, OSARGs can be made into a standard candle as competitive as commonly used Cepheids or Miras, but much more numerous.

Project description:

This is a data analysis oriented project with elements of machine learning.

Background:

Standard candles are objects whose intrinsic luminosity is known a-priori, and as reliable distance indicators they are quintessential for our charting of the Universe. In the Galaxy, pulsating stars located along the instability strip – Miras, Cepheis and RR Lyrae - are typically used as standard candles. Unfortunately, these pulsators are rather rare; moreover they are a biased tracer of the underlying stellar population. For example, Cepheids are young and metal rich, while RR Lyrae are typically old and metal poor. In this Project, we propose to investigate the utility of a different kind of a standard candle – the OGLE Small Amplitude Red Giant stars or OSARGs. The amplitudes of the OSARG flux variability are small (as obvious from the name itself) and the reason of their pulsation is unclear (Soszynski et al 2007). Moreover, unlike the classical pulsating stars mentioned above, OSARGs are quasi-periodic, meaning that their Fourier spectra contain multiple harmonics with similar amplitudes rather than a single dominant one. Nonetheless, most importantly, OSARGs conform to well-defined period-luminosity sequences just like the conventional standard candles (see Figure 1) and thus can (with a bit of work) be used as distance indicators. Better still, OSARGs are more numerous than other conventional standard candles and have smaller scatter around the P-L relation. As part of this project, the student will use the ZTF DR1 data to identify OSARG variables in the Galaxy, measure their light-curve shapes and assign distances. The primary application for this un-biased set of distance tracers is the mapping of the Galaxy at high latitudes. Most recently, it has been shown that at large distances from the Milky Way’s disc, there exists a mix of stellar populations with a wide range of metallicities and ages. This is at odds with the established picture of the high-latitude region of the Galaxy being dominated by the old and metal-poor halo stars. For example, the last major merger event (see Belokurov et al 2018) have heated the Galaxy’s proto-disc stars on highly eccentric orbits thus populating the halo with old and metal-rich stars. On the other hand, the recent interactions between the Sagittarius dwarf and the disc have been shown to kick up some of he young and metal-enhanced stars.
Project details:
The student will identify OSARGs in the ZTF data. This is accomplished by either selecting RGB stars from spectroscopic datasets such SDSS and/or LAMOST and then looking for significant variability or by detecting OSARGs based on the lightcurve shapes. The ZTF data will be accessed via SQL interface using the IoA’s local Whole Sky Database (WSDB). As clear from Figure 1, between 3 to 4 sequences corresponding to pulsating RGBs can be seen in the period-luminosity space. To identify which P-L relation a particular star sits on, we propose to employ the method devised by Rau et al (2019), who used a Machine Learning technique known as Random Forest to assign OSARGs to appropriate P-L sequences. Additionally, we propose to investigate the dependence of the OSARG’s lightcurve shape features on the stellar metallicity and/or age.

Skills required:
Skills: SQL, programming in Python (or IDL)

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

https://ui.adsabs.harvard.edu/abs/2007AcA....57..201S/abstract

“Calibrating long-period variables as standard candles with machine learning” by Rau et al 2019
https://ui.adsabs.harvard.edu/abs/2019MNRAS.484..409R/abstract

General references: (List papers referred to in the project description)
“Co-formation of the disc and the stellar halo” by Belokurov et al 2018
https://ui.adsabs.harvard.edu/abs/2018MNRAS.478..611B/abstract

“The influence of Sagittarius and the Large Magellanic Cloud on the stellar disc of the Milky Way Galaxy” by Laporte et al 2018
https://ui.adsabs.harvard.edu/abs/2018MNRAS.481..286L/abstract

“Two chemically similar stellar overdensities on opposite sides of the plane of the Galactic disk” by Bergemann et al 2018
https://ui.adsabs.harvard.edu/abs/2018Natur.555..334B/abstract
3. Galaxy’s mass and assembly history from phase-space clump focusing

Supervisor I: Vasily Belokurov, H20, Vasily@ast.cam.ac.uk
Supervisor II: Wyn Evans, nwe@ast.cam.ac.uk/Jason Sanders, jls@ast.cam.ac.uk
UTO: Vasily Belokurov

Project summary:

When satellites disrupt in the gravitational potential of the Milky Way, their stars fill in a large volume in the Galactic halo as the tidal debris phase-mix. However, in the phase space or integrals-of-motion space, the satellite’s particles will remain highly clustered for many billions of years as a consequence of the Liouville's theorem. In the integrals-of-motion space, these debris clumps will appear tighter (more focused) when the integrals are calculated in the gravitational potential closely resembling the true force field of the Galaxy. This property can be exploited to measure the Galactic density distribution, which is dominated by Dark Matter. When limited to a small volume of the Galactic halo, tidal clumps deposited by a large satellite break up into a grid of small patches, where the number of patches is directly proportional to the time the debris have been phase-mixing in the Galaxy. This patchy nature of localised tidal debris can be used to measure the accretion times of massive mergers and thus reconstruct the Galaxy's accretion history. In this project, the student will study the analytic properties of tidal clumps, run test particle simulations to produce realistic clump distributions. Using these, the student will come up with a method to constrain the gravitational potential based on the tightness of a clump in the integrals-of-motion space and/or build an algorithm to estimate the number of patches in the localised tidal debris distribution to measure the duration of disruption. These methods will be tested either using Cosmological simulations of galaxy formation or via application to the Gaia DR2 data. The project comprises of analytic, simulations and data analysis components, the balance between which can be adjusted depending on the student’s skills and interests.

Project description:

The Project applies basic principles from Galactic Dynamics to modelling of the stellar halo sub-structure in the integral-of-motion and/or phase space. We would like to pursue ideas that have already been discussed in detail in the literature, yet no working implementation has been presented so far (but see Yang et al 2019).

Background:

A revolution is under way in the field of Galactic Astronomy enabled by the releases of unprecedented (in scope and quality) data from the ESA’s Gaia space observatory. With this data in hand, the Dark Matter distribution and the accretion history of the Milky Way are being determined. To pin down the Galaxy’s gravitational potential several methods have been put forward, each working with a particular set of assumptions and thus festooned with its own set of degeneracies. In this Project, we will consider a method to constrain the gravitational potential of the Galaxy, i) using a minimal set of assumptions and ii) highly complementary to other conventional techniques. Our method takes advantage of the highly clustered nature of the distribution of tidal debris in the phase space and integrals-of-motion space. Stars tidally stripped from a disrupting satellite can fill a large volume around the host galaxy but will remain tightly clustered in the space spanned by energy and angular momenta, or better still by adiabatic invariants such as actions. In a small, local volume these clustering also reveals itself in the phase space, which does not require an assumption
of the underlying potential. It can be demonstrated that the tidal clumps get blurred if the incorrect potential is assumed when calculating integrals of motion. Thus by iteratively varying gravitational potential and focusing the clumps, the best Galaxy model can be found (see Figure 1).

An alternative version of the project can also be formulated where one considers only a small local volume of the Galaxy. In this case, each clump of tidal debris will break into a network of smaller patches. This is due to the fact that only stars with particular orbital properties can enter the small local volume at given time. The number of these patches is directly proportional to the time the satellite’s stars spent in the host’s potential phase-mixing. Therefore, by estimating the number of patches corresponding to one accretion event, we should be able to measure the duration of the satellite’s disruption (see Figure 2).

Project details: This Project can be taken along two independent but related routes.

**Route 1.** Gravitational potential from clump focusing. In this version, the student will run simple test particle simulations of satellite disruption. Using these, a chosen version of the algorithm to constrain the Galaxy’s gravitational potential as described in any of the following works: McMillan & Binney (2008), Penarrubia et al (2012) or Sanderson et al (2017) will be implemented. The student is also encouraged to come up with their own version of the algorithm. At the next step, the student will either apply the algorithm to the mock data from the Cosmological zoom-in simulations (using in-house simulations or public mocks from Aquarius, Aurigaia and Latte) or to the Gaia DR2 data (with spectroscopy). Note that a number of clumps and streams have already been identified in the Gaia DR2 by e.g. Myeong et al (2018), thus providing ready-to-use dataset to play with.
Route 2. Accretion event timing from local debris patchwork. In this version, the student will run a simulation of satellite disruption, isolate a small local volume and measure the degree of patchiness. Then a version of the algorithm described in Gomez & Helmi (2012) can be implemented and applied to the dataset containing debris from multiple disruption events. The main objective here is understand how the sub-clump detection behaves in the presence of multiple accretion events and/or as applied to realistic data. For the latter, we will look at the tidal debris from the Gaia Sausage (Belokurov et al 2018) and Sequoia events (Myeong et al 2019) that dominate the stellar halo in the Solar neighbourhood.

Skills required:
Lecture courses: Galactic Dynamics (e.g. Part II's Stellar Dynamics and Structure of Galaxies). Skills: programming

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

“Disassembling the Galaxy with angle-action coordinates” by McMillan & Binney 2008
https://ui.adsabs.harvard.edu/abs/2008MNRAS.390..429M/abstract

“On the identification of substructure in phase space using orbital frequencies” by Gomez & Helmi 2010
https://ui.adsabs.harvard.edu/abs/2010MNRAS.401.2285G/abstract

“Modeling the Gravitational Potential of a Cosmological Dark Matter Halo with Stellar Streams” by Sanderson et al 2017

“Co-formation of the disc and the stellar halo” by Belokurov et al 2018
https://ui.adsabs.harvard.edu/abs/2018MNRAS.478..611B/abstract

“Halo substructure in the SDSS-Gaia catalogue: streams and clumps” by Myeong et al 2018
https://ui.adsabs.harvard.edu/abs/2018MNRAS.475.1537M/abstract

“Evidence for two early accretion events that built the Milky Way stellar halo” by Myeong et al 2019
https://ui.adsabs.harvard.edu/abs/2019MNRAS.488.1235M/abstract

General references: (List papers referred to in the project description)

https://ui.adsabs.harvard.edu/abs/2012ApJ...760....2P/abstract

“Action-space Clustering of Tidal Streams to Infer the Galactic Potential” by Sanderson et al 2015
https://ui.adsabs.harvard.edu/abs/2015ApJ...801...98S/abstract

“Applying Liouville's Theorem to Gaia Data” by Buckley et al 2019

“Gravitational Potential from small-scale clustering in action space: Application to Gaia DR2” by Yang et al 2019
4. Picking up shells

Supervisor I: Vasily Belokurov, H2O, Vasily@ast.cam.ac.uk
Supervisor II: Wyn Evans, nwe@ast.cam.ac.uk/Eugene Vasiliev, vasiliev@ast.cam.ac.uk
UTO: Vasily Belokurov

Project summary:
A massive satellite disrupting on a nearly radial orbit leaves behind a battery of shells – concentric caustic-like stellar over-densities. These are easy to see in other galaxies, but are notoriously difficult to pick up in the Milky Way. This is because, given our vantage point in the Galaxy, such shells will cover large areas of the sky, thus yielding low detection contrast. Most recently, using Gaia data we have discovered several unmistaken signs that a massive dwarf satellite did collide almost head-on with our Galaxy some 10 billion years ago producing a stellar halo over-density dubbed the Gaia Sausage. In this Project, the student will use Gaia DR2 data to find the debris shells produced as a result of this merger. If detected, these will help to constrain the properties of the Gaia Sausage accretion event.

Project description:
The Project combines ideas from Galactic Dynamics with innovative data analysis techniques which are tested by running and analysing numerical N-body simulations.

Background:
Tidal shells are produced when a massive satellite collides with its host galaxy on an orbit with a low impact parameter. Each peri-centric passage produces a well-defined "shell" of stellar tidal debris, which subsequently continues to move (mostly) radially in the host's gravitational potential. An example of shell formation around galaxy NGC 4651 is presented in Figure 1. In the Milky Way, such shells are not easy to detect given the Sun's position only 8 kpc away from the Galactic centre. We expect however, that there should be several such shells in the Galaxy, in particular those left behind by the Gaia Sausage merger (see Belokurov et al 2018). If these shells are detected, analysis of their properties will help to constrain the details of the Gaia Sausage merger, such as its mass and the time of accretion (see Sanderson and Helmi 2013).
Project details:

The aim of the Project is to detect shells of tidal debris from the Gaia Sausage merger using the Gaia DR2 data. The student will query the IoA’s local all-sky survey database WSDB using Structured Query Language (SQL). The shells should appear as density enhancements in the radial profile of the Galactic stellar halo. To build such a radial density profile, stars with good distance estimates are required. The student will use RR Lyrae available as part of the Gaia DR2. For the purposes of this project, RR Lyrae can be considered standard candles, with distance uncertainties of order of 10%. To enhance the signal-to-noise, we envisage complementing the RR Lyrae sample with Blue Horizontal Branch (BHB) stars that can be extracted from the SDSS using a combination of cuts in the color-color space spanned by $ugri$ magnitudes. Alternatively BHBs can selected using $grz$ magnitudes in the data from DES, PS1 or DECaLS surveys (see Figure 2 and Deason et al 2011; Li et al 2019). Finally, the shell detectability can be increased by i) modelling the underlying stellar halo radial density profile (see Deason et al 2011) and by ii) measuring the phase-space density in each radial bin rather than simply the spatial density. The student will implement phase-space density estimation for the selected set of standard candles (RR Lyrae and BHBs) using the published methods such as FIESTAS (Ascasibar & Binney) and EnBid (Sharma & Steinmetz 2006). Before applying the shell detection machinery to the real (Gaia DR2) data, we envisage testing it on the mock stellar halo created by running numerical simulations of dwarf galaxies disruption.

Skills required:
Lecture courses: Galactic Dynamics (e.g. Part II’s Stellar Dynamics and Structure of Galaxies). Skills: SQL, programming in Python (or IDL)

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

“Co-formation of the disc and the stellar halo” by Belokurov et al 2018
https://ui.adsabs.harvard.edu/abs/2018MNRAS.478..611B/abstract

“An analytical phase-space model for tidal caustics” by Sanderson & Helmi 2013
Numerical estimation of densities" by Ascasibar & Binney 2005
https://ui.adsabs.harvard.edu/abs/2005MNRAS.356..872A/abstract

"Multidimensional density estimation and phase-space structure of dark matter haloes" by Sharma & Stenmetz 2006
https://ui.adsabs.harvard.edu/abs/2006MNRAS.373.1293S/abstract

General references: (List papers referred to in the project description)

“The Milky Way stellar halo out to 40 kpc: squashed, broken but smooth” by Deason et al 2011
https://ui.adsabs.harvard.edu/abs/2011MNRAS.416.2903D/abstract

“The Southern Stellar Stream Spectroscopic Survey (S5): Overview, Target Selection, Data Reduction, Validation, and Early Science” by Li et al 2019
# 5. Quasar variability with ZTF and Gaia for Cosmology

### Project summary:

Quasars are the most luminous objects in the Universe and can be seen across a wide range of distances (redshifts). It has been known for some time that a QSO’s optical variability depends on its luminosity, with lower luminosity objects exhibiting flux changes with larger amplitude. However, no detailed study of the QSO optical variability has been conducted so far due to lack of wide-area multi-epoch data. In the last year, the situation has changed dramatically with the release of all-sky photometry from the Gaia space observatory and the first wide-area data release from the Zwicky Transient Factory (ZTF). This Project takes advantage of the order of magnitude increase in the available data to study the optical variability of QSOs. The Project will look at the suitability of QSO for Hubble diagram building and thus for Cosmological probes alongside Supernovae Ia.

### Project description:

This is an Observational Cosmology Project which is largely data analysis oriented.

### Background:

All quasars (QSO) change their brightness. This intrinsic QSO variability has not yet been studied in detail, although recent years have seen increased interest in the properties of the so-called “changing look” QSOs, i.e. objects undergoing dramatic (more than 1 mag) change in brightness alongside spectacular changes in the their spectra (see e.g. MacLeod et al 2016). Early studies of the QSO optical variability detected a clear correlation between the amplitude of flux changes and the luminosity of the quasar (see e.g. Hook et al 1994). The lower luminosity QSOs were observed to have higher amplitude changes in their flux. Such correlation can be used to build a QSO-based Hubble diagram similar to that constructed using Supernova Ia (see e.g. Perlmutter et al 1999) to study the expansion of the Universe. This project will analyse the QSO optical variability as measured by Gaia and ZTF. Figure 1 shows the properties of QSO in the catalogue of Veron et al (2010) as measured by Gaia DR2. In particular, left panel shows the density of QSOs in the plane of redshift and Gaia G magnitude. It is clear that Gaia can easily detect quasars as far as z=4. The middle panel shows the dependence of the luminosity of the Gaia-detected QSOs on their redshift, which shows that – unsurprisingly - the low-luminosity QSOs can only be detected at low redshifts and the high redshifts are probed by luminous objects. This is the consequence of the Gaia DR2 catalogue being a flux limited sample. Finally, the right panel displays the correlation between the QSO variability amplitude and their luminosity. Here the variability amplitude is defined as in Belokurov et al (2017) but we also subtract the mean error as a function of magnitude.
Figure 1. Properties of QSO from Veron et al (2010) catalogue as seen by Gaia (DR2). Left: QSO redshift as a function of Gaia G magnitude. Middle: QSO luminosity as a function of redshift. Right: QSO variability amplitude as a function of QSO luminosity

Project details:
The student will start by cross-matching the SDSS DR14 QSO catalogue (Paris et al 2018) with ZTF and Gaia DR2 catalogues by running SQL queries on the IoA's local WSDB database. Using these, the QSO optical variability properties similar to those shown in Figure 1 will be analysed. The student will investigate how to take the redshift evolution of the variability into account when inferring the QSO luminosity (time dilation, k-correction). To tighten up the variability-luminosity diagram, flux measurements in different pass-bands might need to be taken into account. The student will also explore whether other QSO properties (such as the strengths of absorption/emission lines) can help to improve the above correlation. Finally, the student should attempt making the QSO-based Hubble diagram (see Risaliti et al 2018 for similar ideas) and estimate the uncertainty in the inference of the parameters controlling the expansion of the Universe.

Skills required:
Skills: SQL, programming in Python (or IDL)

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

“The Variability of Optically Selected Quasars” by Hook et al 1994
http://adsabs.harvard.edu/abs/1994MNRAS.268..305H

“Clouds, Streams and Bridges. Redrawing the blueprint of the Magellanic System with Gaia DR1” by Belokurov et al 2017
https://ui.adsabs.harvard.edu/abs/2017MNRAS.466.4711B/abstract

“The Sloan Digital Sky Survey Quasar Catalog: Fourteenth data release” by Paris et al 2018
https://ui.adsabs.harvard.edu/abs/2018A%26A...613A..51P/abstract

“Cosmological Constraints from the Hubble Diagram of Quasars at High Redshifts” by Risaliti et al 2019
https://ui.adsabs.harvard.edu/abs/2019NatAs...3..272R/abstract

General references: (List papers referred to in the project description)
“A systematic search for changing-look quasars in SDSS” by MacLeod et al 2016
https://ui.adsabs.harvard.edu/abs/2016MNRAS.457..389M/abstract

“Measurements of Ω and Λ from 42 High-Redshift Supernovae” by Perlmutter et al 1999

“A catalogue of quasars and active nuclei: 13th edition” by Veron et al 2010
https://ui.adsabs.harvard.edu/abs/2010A%26A...518A..10V/abstract
6. The Geology of Exoplanetary Systems

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

Project summary:
The presence of short-lived radioactive nuclides in our Solar System provides the internal heat required to melt and differentiate rocky planetary bodies. Do the same processes occur in exoplanetary systems? In an era when we are just starting to characterise rocky Earth-like exoplanets, it is incredible that we are able to start to probe such geological processes. This project will link a unique set of observations of white dwarfs that have accreted planetary bodies to models for star formation.

Project description:
The project is theoretical in nature and ideally suited to a student interested in developing expertise in matching models to observations. An interest in exoplanetary systems is key.

Background:
In the next decades we will detect hundreds of rocky exo-planets, with up-coming space and ground-based missions, such as PLATO. These observations can tell us the planet radius, and where multiple observations exist, the planet mass. State of the art observations are starting to probe the atmospheres of super-Earths. Earth's history is dominated by geological processes. Can we study the geology of these other worlds today?

A unique opportunity is presented by observations of planetary bodies that have ended their lives inside the atmospheres of white dwarfs, the faint stellar remnants of stars like our Sun. We can observe the composition of these planetary bodies in terms of key rock-forming species such as magnesium, iron and calcium in the spectra of the white dwarf. The white dwarf atmosphere should, otherwise, be purely helium or hydrogen. These observations provide the first insights into geological processes that occur in rocky exo-planetary bodies.

Over two hundred white dwarfs have now been detected where both Ca and Fe are detected (e.g. Hollands et al, 2017, 2018), whilst more than five elements have been detected for more than 20 white dwarfs (Harrison et al, 2018). Many of these white dwarfs, known as polluted white dwarfs, show evidence for over abundances of either siderophile (iron-loving) or lithophile species. These have been interpreted as white dwarfs that have accreted fragments of a larger planetary body that differentiated to form a core and a mantle. The key question is, however, what fraction of exoplanetesimals really differentiate?
In our Solar System the differentiation of many rocky bodies is best understood when additional heating from the decay of short-lived radioactive nuclides is considered. Such short-lived radioactive nuclides are produced in massive stars, which must have polluted the Sun-forming region, either from the winds of massive Wolf-Rayet stars or supernovae (Young et al, 2014, Gaidos et al, 2009). The critical question is whether every exo-planetary system is enhanced in short-lived radioactive nuclides, or is our Solar System a special case?

**Project details:**
This project aims to predict the range of Ca/Fe ratios that should occur in polluted white dwarfs, based on the presence of short-lived radioactive nuclides predicted from simulations of star formation (Fig 1, Lichtenberg et al, 2016).

1) The distribution of short-lived radioactive nuclides predicted from simulations of star formation will be used to predict the range of diameters at which rocky planetary bodies can differentiate. This model will assume a single formation time for all bodies.

2) Create a simple model for the size distribution of fragments in exoplanetesimal belts

3) Models from 1) and 2) will be used to predict the distribution of Ca/Fe ratios accreted by white dwarfs.

4) The predictions will be compared to the observed population (e.g. Fig 2 Hollands et al, 2017) and Markov Chain Monte Carlo (MCMC) fitting used to determine the most likely values of the model parameters.

5) If time allows, the model could be improved to investigate how important the time of formation of the planetesimals for the process of differentiation. Predictions will be made as to how various simple models for formation time as a function of size and belt location influence the population of pollutants accreted by white dwarfs.

**Skills required:**
Attendance of the Exoplanets lecture course, the Planetary Systems Dynamics lecture course and/or the Stars lecture course would be beneficial, but are not a necessity. Basic courses in Earth sciences would also help. Basic programming skills e.g. Python

**Useful references:**

**General references:**
Fig1: Predictions for the presence of short-lived radioactive nuclides in exoplanetary systems and thus, the radiogenic heating, based on simulations of star formation. Lichtenberg et al, 2016

Fig2: An example of white dwarf that has accreted a planetary body rich in iron, magnesium, calcium etc. Hollands et al, 2017
7. Testing dust evolution in protoplanetary discs

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UTO: Cathie Clarke (H10, cclarke@ast.cam.ac.uk)

**Project summary:**
Planetary formation begins with grain growth in protoplanetary discs, yet today our theoretical understanding of the evolution of dust grains in discs lags behind observational data. ALMA surveys in nearby star forming regions provide constraints on the mass of dust and the grain sizes throughout the lifetime of discs (e.g. Ansdell et al. 2016;2017). In this project you will explore the evolution dust masses and grain sizes using a modern dust evolution code (Booth et al. 2017) and compare the results to the observed properties of discs. In this way you will test models of grain growth to determine the factors that ultimately control the evolution of dust, the earliest phase of planet formation.

**Project description:**

**Background:**
Planet formation begins with the growth of dust grains from the sub-micron sizes seen in the interstellar medium to millimetre or centimetre sizes in planet forming discs. We now know that pebbles (mm- to cm-sized dust grains) play an essential role in planet formation, controlling the formation of planetary embryos, accelerating their growth into planets, and even driving changes in the composition of planet-forming discs. We can now study the properties of dust in protoplanetary discs with The Atacama Large Millimeter Array (ALMA), which can resolve the thermal emission from dust grains in discs. ALMA has shown us that in even the youngest discs the spatial distribution of dust grains is affected by the presence of planets (Clarke et al. 2018), making it clear that planet formation occurs alongside the evolution of discs. Understanding dust evolution is now essential to understand planet formation.

The aim of this project is to confront the state-of-the-art theoretical models for dust evolution, which form the basis for numerous planet formation studies, with observations of protoplanetary discs. With ALMA, we now have complete surveys of protoplanetary discs across a range of ages, providing estimates of the dust mass throughout the disc lifetime (Ansdell et al. 2016;2017, see the gallery of images below). For younger regions, such as Taurus and Lupus, multi-wavelength data now offers an opportunity to probe the size of grains with a higher fidelity (e.g. Ricci et al. 2010). These unprecedented large samples of disc observations enable new ways of testing dust evolution models, i.e. using statistics through grids of models rather than fine-tuned studies of single objects.

**Project details:**
The aim of the project is to confront grain growth models with observations of protoplanetary discs to determine the factors that control the evolution of dust in discs. Our current understanding of dust evolution is that grains grow through collisions until they reach a barrier to growth: bouncing, fragmentation or radial drift (e.g. Birnstiel 2012). However, the details of these processes remain poorly understood and the default assumptions struggle to reproduce the observed disc properties. You will use a modern
dust evolution code to explore whether varying the assumptions behind these models can help to reconcile the differences between theory and observations.

Your first task will be to construct a population of models, varying different assumptions about the disc properties (e.g. size, mass, viscosity) and dust evolution parameters (e.g. strength against fragmentation, growth rate). By generating simulated ALMA observations, you will compare these models to ALMA surveys and use them to determine that factors that control the evolution.

Initially we will focus on reproducing:

1. The evolution of disc masses as measured by their millimetre flux
2. The spectral index of the emission in Taurus / Lupus to calibrate the grain sizes.

Other aspects of the problem that can be investigated given your interests are:

- What is the underlying population of disc properties?
- What are the implications for planet formation?
- What are the implications for disc chemical evolution?

![Fig 1: Millimetre emission from the Lupus discs survey](image)

Skills required:
The student will need to use a code written in python. Familiarity with python or a desire to learn python is preferred.

Useful references:

General references:
Testi et al. 2014, Protostars and Planets VI, pp. 339

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8. K2 observations of the polar V358 Aquarii

Supervisor I: Elmé Breedt (H34, ebreedt@ast.cam.ac.uk)
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UTO: Gerry Gilmore (H47, gil@ast.cam.ac.uk)

Project summary:
You will reduce and analyse the light curve of the polar V358 Aqr, update the ephemeris of the binary and investigate the properties of the flaring donor star in this system. Depending on the time and interest of the student, other polars could be included in the study as well.

Project description:
Background:
Polars are a subset of cataclysmic variables – they are binaries in which a strongly magnetic white dwarf accretes material from a nearby M-dwarf companion (Fig 1). In non-magnetic cataclysmic variables, the material from the companion star forms an accretion disc around the white dwarf before it is accreted, but in polars, the strong magnetic field of the white dwarf completely prevents a disc from forming. The ionised plasma is threaded onto the magnetic field lines when it reaches the L1 point, from where it is accelerated directly onto the white dwarf surface. Roughly one-third of cataclysmic variable binaries appear to host a magnetic white dwarf, a much higher incidence than seen in isolated white dwarfs (few percent) [1]. Detached magnetic white dwarfs plus M-dwarf companions are almost completely unheard of [2], so why are there so many magnetic CVs? The answer is still unknown but it shows that studying the properties of polars is important, to determine the influence of the magnetic field on the evolution of binary stars.

Project details:
As is the case for many polars, V358 Aqr was discovered as a result of its X-ray emission [3]. In many ways it is a standard polar, but previous observations [4] have shown that the donor star in this system is unusually active, producing large and frequent flares.

During the final campaign of the K2 mission (campaign 19), just before the spacecraft's fuel ran out, Kepler/K2 observed V358 Aqr in short cadence mode: an exposure every minute for two weeks (Fig 2). First you will use the Kepler python tools to extract and clean this light curve, in order to distinguish between donor star flaring and spacecraft noise. (As the fuel was getting low, the spacecraft was less stable than it had been previously. This introduced some spurious variability into the light curve.) Next you will measure and update the ephemeris of the binary, using the K2 data as well as historical observations [4, 8], and investigate the frequency and origin of flares on the donor star of this system.

Polars also exhibit 'high' and 'low' states as the accretion rate changes and the flow at the L1 point switches on and off. If time permits, the two other polars observed by K2 can be included in the study as well. Their light curves are not as well sampled as for V358 Aqr (they have only one observation every 30 min) but it presents an opportunity to compare the properties of polars in high and low accretion states.
Project details (contd.)

Fig 1: Schematic diagram illustrating the main components of a polar. The magnetic field of the white dwarf prevents the formation of an accretion disc and instead funnels the flow directly onto the white dwarf.

Fig 2: A section of the Kepler/K2 light curve of V358 Aqr. The variability at the peaks may be due to stellar flares on the donor star.

Skills required:
Programming experience is not a prerequisite, but will be helpful. The student will be expected to write simple Python programmes for handling, analysing and visualising the data.

Useful references:
9. Searching for Extremely Metal-Poor stars in the Galactic halo with Gaia

Supervisor I: Giorgia Busso (Obs O22, email: giorgia@ast.cam.ac.uk)

Supervisor II: Francesca De Angeli (Obs O23, email: fda@ast.cam.ac.uk)

UTO: Mike Irwin (APM 01, email: mike@ast.cam.ac.uk)

Project summary:
Extremely metal-poor stars (EMPs) are the fossil remnants of the first epoch of star formation in the Universe. As such they provide important clues about the nature of the first stars and their exotic associated supernovae events. Detailed research into the few surviving EMPs is only possible in the Local Universe where these very rare objects lie hidden amongst the plethora of more recent generations of stars. The Galactic Halo and Bulge provide ideal hunting grounds to uncover more examples of EMPs for detailed follow up. We will make use of Gaia Blue and Red (BP and RP respectively) spectra coupled with Gaia DR2 astrometric and photometric data to assess the potential of Gaia to search for EMPs in the Galactic Halo and Bulge.

Background:
The surviving Extremely Metal-Poor stars (EMPs) stars in the Universe are key to understanding the nature of the formation of the first stars and the nucleosynthesis events associated with them. Although the first populations of stars were created at redshifts of z=10 or higher, the lower mass sources should have survived to the present day and exist in prototypical L* galaxies like the Milky Way. Although vastly outnumbered by subsequent star formation events, the best place to look for examples of EMPs is in our own Galactic backyard where proximity enables detailed study and outweighs the disadvantages of the needles in a haystack problem of finding them.

The review by Beers & Christlieb (2005) summarises the various methods employed to search for very metal-deficient stars in our Galaxy and in particular highlights the efficiency of objective prism searches forged by the HK survey of Preston and Beers, and the Hamburg-ESO objective prism survey of Christlieb and colleagues. Remarkably, these early photographic plate-based methods provide spectra quite similar in properties to those generated by the Gaia BP and RP spectrographs.

Gaia (Gaia Collaboration, Prusti et al., 2016) has the big advantage of all-sky coverage, freedom from the effects of the Earth’s atmosphere and direct digitisation and extraction of the spectra. Some of the strongest metal lines in stellar spectra, and hence the most useful for characterising metal deficiency, are the Ca H&K absorption lines at 3933A and 3967A. These are what were targeted by the HK and Hamburg-ESO objective prism surveys and indeed form the basis of more recent successful photometric searches such as PRISTINE (Starkenburg et al. 2017). The Gaia wavelength coverage is approximately 3330-10000A and it should be feasible to detect these spectral features. The recent Gaia DR2 (Gaia...
Collaboration, Brown et al. 2018) contains ~1.4 billion of stars with astrometry (based on 5 parameters) and photometry (G, BP and RP), thus providing a huge laboratory for the research of these peculiar stars.

Project details:

- Literature study of current methods for finding EMPs in the Galactic Halo and Bulge to investigate what aspects of these might be useful for a Gaia-based search. Familiarise with Gaia properties and how to extract information from the ESA database.
- Compile a list of the currently known Galactic EMps and analyse the Gaia DR2 measurements and BP and RP spectra for this sample. Assess if simple metrics provide a reliable way to select out EMP candidates.
- Repeat analysis on large area of Halo and Bulge to analyse contaminant fraction and population types that might pollute sample. Revisit EMP selection criteria to refine robustness against contaminants (specificity) and attempt to retain sensitivity to known examples of EMPs, or candidates selected by other methods (e.g. PRISTINE) in region.
- Cross-correlate candidates with existing spectra such as those available from SDSS or RAVE and compare expected properties with those measurable from these higher resolution spectra.
Skills required:
This project requires some programming/scripting ability and familiarity with basic statistical analysis techniques.
There will be a degree of background reading assessing existing techniques for finding EMPs and some familiarisation with the expected astrophysical properties that characterise the first generation(s) of stars.
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.

Useful references:

10. Evaluating biases from CMB secondary anisotropies to primordial non-Gaussianity measurements

Project summary:
In a recent paper, Hill (2018) showed there are potentially significant biases, that had been previously ignored, to measurements of primordial non-Gaussianity arising from CMB secondary anisotropies. This project will focus on validating the theoretical calculations in Hill (2018) through a set of simulations. Through this work, we will assess how important these biases will be for upcoming experiments and how effective are the existing mitigation strategies.

Project description:
This project will use existing bispectrum measurement tools to study the bias induced by CMB secondary anisotropies on searches for primordial non-Gaussianity. This will be done by estimating the level of non-Gaussianity in simulations that consistently include a range of CMB distortions including weak gravitational lensing, the integrated Sachs–Wolfe effect, the thermal and kinetic Sunyaev–Zel'dovich effects, and the cosmic infrared background.

Background:
A major goal of cosmology is to understand the physics of the early universe. A brief period of cosmic inflation in the very early universe is a compelling idea to explain the generation of the seeds from which all cosmic structure developed. Inflation naturally predicts small primordial fluctuations with statistical properties close to those inferred from observations of the cosmic microwave background (CMB) anisotropies and probes of the clustering of matter in the late-time universe. Simple inflation models predict the primordial fluctuations should be very nearly Gaussian distributed, but more complex models can produce observable levels of non-Gaussianity (e.g., Chen 2010). Searching for such primordial non-Gaussianity is one of the most promising avenues to reveal the physics of the early universe as it encodes unique information about the field content and their interactions at this epoch. Currently the best method of constraining primordial non-Gaussianity is through measurements of a generalisation of the skewness (known as the bispectrum) of the CMB (Planck Collaboration, 2019).

Observations of the CMB do not only measure fluctuations imprinted at the surface of last scattering (when the universe was around 380,000 years old). The CMB includes additional imprints, known as secondary anisotropies, which are sourced as the CMB photons propagate through the clustered matter between the last-scattering surface and our location. Examples of secondary anisotropies are weak gravitational lensing by large-scale structures, the integrated Sachs–Wolfe (ISW) effect, where the energy of CMB photons is changed by traversing time-varying gravitational potentials, and the Sunyaev–Zel'dovich effects (tSZ and kSZ), the scattering of CMB photons by electrons in galaxy clusters. In addition, CMB observations may be contaminated by residual emission from galaxies, e.g., the cosmic infrared background (CIB).

Most work to date has focused on studying how one particular combination of these effects, the ISW and lensing effects (see, e.g., Lewis et al, 2011), can bias measurements of primordial non-Gaussianity. However recent work by Hill (2018) has shown that a wide range of other combinations could bias measurements of primordial non-Gaussianity. These
include combinations such as lensing-tSZ and ISW-tSZ-tSZ, and many others. This project will focus on using existing simulations of these effects to assess their impact on measurements of primordial non-Gaussianity.

Project details:
The student will mainly use a set of existing bispectrum measurement tools, developed primarily by the supervisors and Professor Daan Meerburg. These tools will be applied to the WebSky\(^1\) suite of simulations, a subset of which are shown in Figure 1. These simulations contain the main CMB secondary anisotropies (ISW, tSZ, kSZ, and gravitational lensing) along with the CIB, and include the correct correlations between them, which is vital for this project.

The first part of this project will be to assess the levels of bias introduced by the different effects and compare these to the analytical calculations of Hill (2018). This will involve applying the existing bispectrum codes to the simulations and then, qualitatively, comparing these measurements to the results of Hill (2018). The results obtained can then be used to assess the impact for current measurements, such as from Planck, and for future experiments, such as the Simons Observatory.

The next part of the project will be to see how combining observations at multiple frequencies (a process known as foreground cleaning) can help mitigate the biases. For Planck, this will involve using the particular (SMICA) frequency combinations as a function of angular scale used in the analysis of Planck Collaboration (2019). It will be of great interest to see if these foreground cleaning techniques are sufficient or if significant biases still remain.

This project is well suited to a student interested in future studies in cosmology, as through the project the student will be exposed to topics ranging from the very early universe to large-scale structure in the late-time, evolved universe. In parallel, the student will become familiar with the basic statistical methods used in cosmology.

Figure 1: The Figure on the left shows a realization of the WebSky simulations. There are four maps showing, in a clockwise manner from the top left, the thermal Sunyaev Zel’dovich emission, the kinetic Sunyaev Zel’dovich emission, cosmic infra-red background emission and the lensing anisotropies. The Figure on the right is a visualization of the CMB bispectrum as measured by the Planck Satellite. In the project we wish to see how the

\(^1\) https://mocks.cita.utoronto.ca/index.php/WebSky_Extragalactic_CMB_Mocks
bispectrum of the maps on the left compare to, and impact, primordial CMB bispectrum measurements.

Skills required:
The student will be expected to use existing codes written in Python and Fortran and have the capability to extend these as needed. Basic familiarity with Linux-based systems will be useful. A high level of mathematical and computational skills is required.

Relevant lecture courses: Cosmology, Advanced Cosmology, Formation of Structure in the Universe.

Useful references:

*Introductions to primordial non-Gaussianity:*

*Current state-of-the-art measurements of primordial non-Gaussianity:*
Planck Collaboration, 2019, arXiv:1905.05697

*A thorough summary of the ISW-lensing bias to primordial non-Gaussianity:*

*Recent work highlighting other biases to primordial non-Gaussianity:*
11. Line Driven Wind Variability from Accreting α−Discs

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**Supervisor II:**

**UTO:** Prof. Chris Reynolds, (Hoyle 15, csr12@ast.cam.ac.uk)

**Project summary:** Line driving is a possible mechanism for launching outflows in a variety of systems with accretion discs such as cataclysmic variables (CVs) and active galactic nuclei (AGN). An important question is establishing the connection between variability in the accretion flow and the corresponding radiatively driven wind. We will use hydrodynamics (HD) simulations to study two main questions 1) How does a line driven wind alter accretion disc structure? 2) How does accretion rate variability produce spatial and temporal variability in the outflow?

**Project description:** We will use the magnetohydrodynamics (MHD) code Athena++ to simulate line driven disc winds from cataclysmic variables (CVs). Accretion in the disc will be driven via a standard Shakura-Sunyaev α−disc prescription and the corresponding disc luminosity computed self-consistently from the local accretion rate (see Pringle 1981 for example). We will compute the radiation force due to spectral lines from the disc on the gas above it in the Sobolev approximation (see Castor, Abbott & Klein 1975). This will require merging two modules already developed in our group. The corresponding simulations will be analyzed both theoretically to understand the accretion/outflow physics and to generate some observational diagnostics of interest to observers.

**Background:** A variety of astrophysical systems, spanning eight orders in mass scale, from massive stars up to active galactic nuclei (AGN), exhibit outflowing material. An important question to address is what physical mechanism is responsible for launching these outflows? One potential driving mechanism for massive stars, CVs and AGN is radiation pressure due to spectral lines, so called line driving. At suitable temperatures and ionization states there are potentially $\sim 10^2$ – $10^3$ s optically thick spectral lines, allowing sub-Eddington luminosity objects to overcome the inward force of gravity and launch outflows.

Disc systems are particularly interesting because the physics governing the outflow can potentially be tied to the physics of accretion. Simulations have shown that the mass flux of line driven winds is to zeroth order set by the system luminosity. Outflowing gas carries angular momentum and energy away from the accretion disc, enhancing accretion in the disc and increasing system luminosity. This increased disc luminosity can in turn increase the strength of the outflows and further drive accretion. Variability in the accretion rate in the disc can therefore lead to variability in the outflow as a they are coupled via the radiation field.

Line driven disc wind simulations to date have used a static disc boundary as a matter reservoir and assumed a radiating thin disc as a source of driving flux. Disc wind simulations have shown that line driving produces both poloidal (in 2D axisymmetry; Proga et al 1998) and toroidal (in 3D; Dyda & Proga 2018a) structures. Further simulations of time-varying radiation fields have shown that density features can likewise be produced at the wind base (Dyda & Proga 2018b). We will relax the assumption of a static thin disc boundary and simulate disc accretion using an α−prescription (see Pringle 1981 for a review). This will allow a non-trivial coupling between the disc accretion and the resulting outflow via the radiation field.
**Project details:** The student will use the MHD code Athena++ to produce 2D simulations of line driven disc winds. This will involve merging two physics modules developed in our group to study line driven winds from thin discs (Dyda & Proga 2018a) and radiating accretion discs (Dyda & Reynolds 2019 in prep). The central questions are 1) How does a line driven wind affect the accretion disc structure 2) How does variability in the accretion rate drive spatial and temporal variability in the outflow? The simulations will be analyzed both theoretically to understand the correlation between outflow (mass flux, velocity, density, etc...) and accretion disc (mass flux, luminosity, etc...) We will then produce a variety of observational diagnostics such as absorption measure distribution and line profiles (Robinson & Dyda 2019, in prep).

**Figure 1:** Left - Density (gray scale) and velocity (black vectors) of 3D line driven disc wind simulation of a CV (Dyda & Proga 2018a). Upper Right- Accretion rate (solid line) and mean accretion rate (dashed line) for thin discs with $\alpha = 0$ (black), $10^{-3}$ (red) and $10^{-2}$ (green) (Dyda & Reynolds in prep). Lower Right - Column density along different $\phi$ sightlines (color lines) and $\phi-$averaged (black) for CV wind (Dyda & Proga 2018a).

**Skills required:** This project is primarily computational in nature - the Athena++ HD simulations will be performed in C++ and further analysis using Python. Basic linux usage will also be required to run the simulations on the local computing cluster. The student will work closely with the CoI (Dyda) and PI (Reynolds) and will have the opportunity to participate in the activities of the X-ray group here at the IoA.

**Useful references:**
12. Is the $H_0$ measurement from Cepheids robust?

Supervisor I: George Efstathiou (K15)  gpe@ast.cam.ac.uk  
Supervisor II:  
UTO:  George Efstathiou

Project summary: Observations of the cosmic microwave background radiation (CMB) are in beautiful agreement with the $\Lambda$CDM cosmology. The best-fit CMB value of the Hubble constant, $H_0$, differs by about $4.4\sigma$ from the value measured in the late time Universe from Cepheid measurements of Type Ia supernova host galaxies. This discrepancy has led to speculations that we may be missing exotic new physics and has become a topic of much interest over the last year. However, the discrepancy may simply reflect systematic errors in the Cepheid measurements. The aim of this project is to compare the slopes of the Riess etal (2016) Cepheid period luminosity relations with well measured slopes in nearby galaxies and to investigate the impact of different slopes on the Riess etal determination of $H_0$. The student will be expected to make construct Monte-Carlo models to assess the impact of possible systematic errors in the Cepheid photometry.

Project description:

Background: The latest results from the Planck satellite give $H_0= 67.4 \pm 0.5$ km/s/Mpc assuming the $\Lambda$CDM cosmology. In contrast, ‘traditional’ distance ladder measurements of $H_0$ appear to give a higher values. In a series of papers, Riess and collaborators have reported Cepheid/supernova measurements of $H_0$ that are increasingly discrepant with the Planck value (Riess etal 2011, 2016, 2018a, 2018b). The latest value of the Riess etal group is $H_0= 74.03 \pm 1.42$ km/s/Mpc, differing from the Planck value by $4.4\sigma$. General arguments suggest that this discrepancy, if real, requires modifications to the early Universe rather than modifications to the late time Universe (see Lemos etal 2019). However, it has proved difficult to find early universe solutions to this problem, though some (rather unnatural) models have been proposed (for a review see Knox and Millea 2019). An alternative explanation is that the Cepheid data are affected in some way by systematic errors. The aim of this project is to perform some internal consistency checks of the Riess etal (2016, herafter R16) Cepheid photometry to check for systematic errors. This will build on earlier work by Efstathiou (2014, herafter E14).

Project details: The main elements of the project are as follows:

(i) Use the best available data on Cepheids to establish the slope of the period-luminosity relation is nearby galaxies, principally, the Large Magellanic Cloud (LMC) and Andromeda. E14 found a slope $b= -3.23 \pm 0.06$.

(ii) Reanalyse the Cepheid photometry of R16. Typically one finds a shallower slope with $b \approx -3.03$, depending on which primary distance anchor (LMC or NGC4258) is included in the fits. An example of a typical period-luminosity relation for one of the R16 galaxies is shown in Fig. 1.

(iii) Establish whether there is a statistically significant difference between the results of (i) and (ii).

(iv) Investigate the impact on $H_0$ of imposing a prior on $b$, as discussed in E14.

(v) Develop an analytic model describing the impact on $H_0$ of imposing a prior on the slope $b$.

(vi) Construct a set of Monte-Carlo models to model systematic errors in the Cepheid photometry that might distort the slope of the period-luminosity relation. Assess
whether the models can reproduce the behaviour seen in the real data.

If time allows it would be useful to reassess the metallicity dependence of the period-luminosity relation using the recent accurate distances estimates to the LMC, NGC4258 (which has an accurate geometric megamaser distance) and Milky Way Cepheids.

**Figure 1:** A Cepheid period-luminosity relation for one of the R16 galaxies (NGC3021). The solid line shows the best fit to the data which has a slope of $b = -2.29 \pm 0.60$. The dashed line shows a fit with the slope constrained to $b = -3.23$. The points are colour coded so that blue (red) points show Cepheids with blue (red) colours.

**Skills required:**

This project would suit a student who is interested in statistics and is mathematically proficient. I would like the student to develop statistics to calculate the statistical significance of parameter shifts derived from correlated datasets.

**Useful references:**

**Project summary:**

The Zwicky Transient Facility scanned more than 3750 square degrees an hour to a depth of 20.5 mag. By repeated imaging of the Northern sky (including the Galactic Plane), it has produced a photometric variability catalogue with nearly 300 observations each year, ideal for studies of all manner of transient phenomena. This database is available in Cambridge, and a suite of summary statistics have already been calculated for the light curves. The aim of the project is to use the statistics to devise ways of efficiently categorising transient phenomena. Particularly interesting are classes of variable stars (such as RR Lyrae or Mira) which can be used as standard candles in galactic astronomy and microlensing events (which can be used to detect black holes, neutron stars and white dwarfs). The aim is therefore to train a powerful machine learning algorithm (such as Random Decision Forests) so as to identify and classify these light curves.

**Project description:**

The Project combines ideas from Galactic Dynamics, Variable Stars & Lensing with innovative data analysis and machine learning techniques.
Background:

The Zwicky Transient Factory is primarily searching for supernovae. As a by-product, it has produced an enormously rich database of ~ 2 billion light curves in the g and r bands. There are all manner of transient phenomena — including variable stars, eclipsing binaries, solar system objects, active galactic nuclei and quasars — in the database. The public data release was made on 8th May 2019. It is very fresh data, and few people have looked through it for treasures. We have incorporated the lightcurves, together with a host of summary statistics, into our whole sky database that is maintained at the Institute of Astronomy, Cambridge. The aim of the project is to identify some classes of variable events which are particularly interesting. This includes, for example, microlensing events.

Figure 1. g and r band light curves of an (unpublished) microlensing event already extracted from the Zwicky Transient Facility data. Notice the time-symmetric, achromatic behaviour of the light curve which are tell-tale microlensing signatures.

Microlensing occurs when a foreground lens passes in front of a background star. Light bending by the theory of relativity causes a temporary amplification in the brightness. This manifests itself as a time-symmetric, achromatic light curve. Fig 1 shows an (unpublished) microlensing event already found in the ZTF data over the Summer by crude techniques. This tells us that a systematic search will yield a rich haul.

Project details:

The aim of the Project is to use a Random Decision Forest Classifier (https://scikit-learn.org/stable/) to identify microlensing events and other variables (eg Dubath et al 2011). Microlensing events are simulated (Paczynski 1986,1996), noise added as well as sampling chosen to mimic the ZTF. This can be used to create say 1000 microlensing events. As microlensing events are rare, any random selection of say 1000 ZTF lightcurves gives a sample of non-microlensing events. These comprise the training set for a Random Decision Forest classifier, which will be trained on summary statistics extracted from the light curves. When run on the entire dataset of 2 billion lightcurves, this will give candidate microlensing events that can be ordered by goodness of fit to the theoretical curve. The classifier can be extended to various classes of variable star, like Miras, by a similar method. Alternatively, some of the individual microlensing events can be studied to understand the nature of the lens and sources by crossmatching the event with other catalogues to find the parallaxes and proper motions In particular, the long timescale events are particularly exciting as black hole candidates.
Skills required:
Lecture courses: Galactic Dynamics (e.g. Part II’s Stellar Dynamics and Structure of Galaxies), Structure and Evolution of Stars. Skills: SQL, programming in Python.

Useful references: (List of important papers/review articles relevant to the project)
“The Zwicky Transient Facility: System Overview, Performance and First Results” by Bellm et al 2019

“The Zwicky Transient Facility” webpage
https://www.ztf.caltech.edu/

General references: (List papers referred to in the project description)
“Gravitational Microlensing by the Galactic Halo” by Paczynski

“Gravitational Microlensing in the Local Group by Paczynski
https://ui.adsabs.harvard.edu/abs/1996ARA%26A..34..419P/abstract

“Random forest automated supervised classification of Periodic variable stars” by Dubath et al.
https://ui.adsabs.harvard.edu/abs/2011MNRAS.414.2602D/abstract
### Project summary:

The 21-cm signal of neutral hydrogen from the first billion years of cosmic evolution is predicted to be a sensitive probe of reionization, primordial star formation and cosmic heating. A first tentative detection of the sky-averaged 21-cm signal was recently announced (EDGES Low Band instrument, Bowman et al. 2018) but has not been confirmed yet. The detected signal is very controversial: it does not comply with standard astrophysical modelling and requires exotic physics. In the framework of this project we will check whether the observed 21-cm signal is consistent with the latest unpublished Cosmic Microwave Background (CMB) polarization data measured by the Planck satellite. Consistency with the CMB data is one of the crucial tests that the EDGES signal has to pass in order to be validated.

### Project description:

This project is extremely timely, it addresses one of the hottest ongoing debates in observational cosmology and makes use of the unique Planck data.

In the framework of this project, polarization of the CMB will be calculated for a large range of underlying high-redshift astrophysical scenarios using a set of reionization histories provided by Fialkov. These theoretical polarization signals will then be compared to the Planck polarization data using likelihood analysis. Some reionization histories will be favoured by the CMB data, others will be ruled out. We will check whether the reionization histories that are consistent with the Planck data are also in agreement with the detected 21-cm signal.

Possible extension of the project includes using the polarization data to derive constraints on high-redshift astrophysical parameters (e.g., star formation efficiency, minimum mass of star forming halos, efficiency of X-ray heating by first black holes).

### Background:

The predicted 21-cm signal of neutral hydrogen (e.g., see Furlanetto et al. 2006 for more details) is the ultimate probe of the Universe between the decoupling of the CMB photons at $z \sim 1100$ and the end of the Epoch of Reionization (EoR) at $z \sim 6$. This signal, produced by neutral hydrogen atoms in the intergalactic medium (IGM), depends on the properties of first stars and black holes which heat and ionize the IGM. Astrophysical properties are poorly known due to the lack of observations, and, as a result, the expected 21-cm signal is not well constrained (Fig 1). However, the future of the 21-cm cosmology is bright, as many existing and planned experiments are targeting this signal. Large international facilities such as the Square Kilometre Array (SKA) will measure fluctuations in the 21-cm signal.
signal, while instruments such as EDGES and SARAS are designed to measure the sky-averaged signal.

The same astrophysical events that drive the 21-cm signal, also affect other cosmic observables. For example, the CMB polarization is influenced by the cosmic reionization history. The Planck satellite has collected exclusive polarization data which has a great potential to constrain the EoR history and, through it, put limits on the expected 21-cm signals. Understanding the implications of Planck’s data on the parameter space of the possible 21-cm signatures is very timely and will guide the low-frequency radio telescopes in their search for the illusive 21-cm signal. Specifically, we can already check if the reported EDGES Low signal is consistent with Planck polarization measurements.

Project details:
The main steps are as follows:

1. Take a compilation of reionization histories and the 21-cm signals calculated by A. Fialkov for a large set of astrophysical parameters (see Fig. 1). The parameters include minimum mass of star forming halos, star formation efficiency, ionization efficiency, heating efficiency, X-ray spectral energy density, mean free path of ionizing photons, amplitude of extra radio background.

2. Use these EoR histories to compute CMB polarization for each combination of the astrophysical parameters. The simplest way will be to plug the EoR histories into the publically available CAMB CMB Boltzmann code.

3. Use the unpublished Planck polarization data (provided by G. Efstathiou and S. Gratton) to compute likelihood of each model.

4. Check if the models that are consistent with the EDGES Low signal are in agreement with the Planck polarization data.

5. Optional: Derive constraints on the astrophysical parameters mentioned in [1]. Plot marginalized probability density for each combination of astrophysical parameters (2D PDF) and for each parameter separately (1D PDF).

Fig. 1: The sky-averaged 21-cm signals as a function of frequency/redshift for 194 different astrophysical models. The colors indicate the ratio between the UV intensity and the X-ray heating rate at the redshift where the signal reaches its minimum. From Cohen et al. (2017).

Skills required:
Proficiency in using either Python or Matlab or C/C++. CAMB is written in Fortran and will require some simple modifications.
Knowledge of statistical methods (likelihood analysis).
Courses: An introductory Cosmology course (at the level of the PartII course) is essential.

Useful references:

Bowman et al. Nature 2018  
https://ui.adsabs.harvard.edu/abs/2018Natur.555...67B/abstract

Astrophysical 21-cm signal  
https://ui.adsabs.harvard.edu/abs/2017MNRAS.472.1915C/abstract

Planck cosmological parameters  
https://arxiv.org/abs/1807.06209  
cosmos.esa.int/web/planck

General references:

Furlanetto et al. 2006  
https://ui.adsabs.harvard.edu/abs/2006PhR...433..181F/abstract
15. How do variations of observing conditions across the sky impact our ability to infer the cosmic density field from galaxy surveys?

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Project summary:
This project looks at two systematic problems in inferring the behaviour of the total cosmic density field from observations of the galaxy density field: The fact that observing conditions of any ground based galaxy survey are not homogeneous across the sky but rather fluctuate as a function of position. And the fact that spectroscopic galaxy surveys can only simultaneously observe galaxies that have a minimum distance on the sky (fibre collisions).

The student will introduce effects that mimic these problems onto simulated galaxy survey data and investigate how that changes the inferred correlation coefficient between galaxy density and total matter density.

Project description:
The matter density field and its evolution on very large scales are a key observable in understanding the behaviour of gravity at cosmological distances. There are, however, observational effects that introduce spurious randomness between the galaxy density field (our primary observable of the cosmic web) and the total matter density field. Observing conditions of ground based galaxy surveys can fluctuate as a function of position. And observational constraints such as the occurrence of fibre collisions in spectroscopic surveys may prevent us from simultaneously observing galaxies that are close-by on the sky.

The student will introduce effects that mimic these two problems onto simulated galaxy survey data and investigate how that changes the inferred correlation coefficient between galaxy density and matter density. Especially, they will determine

- how severely this additional randomness biases our understanding of the relationship between galaxies and the underlying dark matter density field,
- how it should change our interpretation of the distribution of observed cosmic density fluctuations when inferring higher order moments of gravitational collapse.
### Background:

Recent discoveries such as the existence of dark matter or the accelerated expansion of the Universe challenge our understanding of gravity on cosmological scales. An important test of the standard model of cosmology (and the theory of General Relativity on which it is based) is to determine how well it describes the growth of density fluctuations - i.e. the process of gravitational collapse - on very large scales. To do this, one can e.g. compare the amplitude of density fluctuations in the very early Universe (as inferred from observations of the Cosmic Microwave Background, CMB) to the amplitude of density fluctuations observed in today's large scale structure (LSS) of the Universe.

The galaxy density field is a good tracer of the late time LSS since there are only small amounts of (intrinsic) randomness between galaxy and matter density fluctuations (compared to other probes of the LSS such as gravitational lensing). However, while the statistical correlation of matter and galaxy density is quite strong, there is a systematic offset between the two as a result of the complicated processes that drive galaxy formation and evolution. Correct interpretation of the observed galaxy density field hence requires knowledge of this offset which is encoded in the so-called galaxy-bias relation.

When studying the distribution of galaxies with ground based surveys this galaxy-bias relation can be significantly modulated by the fact that observing conditions of the survey (e.g. seeing, sky brightness, air mass) vary across the sky. Also, observational constraints such as a minimum distance of fibres in spectroscopic surveys are imprinted in the observed galaxy density field. Current techniques to deal with these problems are minimising their impact when inferring the amplitude of density fluctuation. However, it has not been investigated how these techniques impact interpretations of higher order moments of the density field. This is of particular importance in a Cambridge-lead effort to study the full probability distribution function (PDF) of cosmic density fluctuations.

### Project details:

The project will consist of the following steps:

A. The student will familiarise themselves with literature about
   - how the relation of matter density and galaxy density can be described in a cosmological context,
   - how variations of observing conditions or observational constraints such as fibre collisions impact cosmological analyses

B. The student will modulate the positions and number density of simulated galaxy samples in order to mimic positional variations of observing conditions and the occurrence of fibre collisions. For this purpose they will be provided with two types of simulated data:
   - simple log-normal realisations of the cosmic matter and galaxy density on the sky,
   - more realistic matter and galaxy density fields from the Buzzard N-body simulation.

   Depending on interest and progress of the project, the student can also learn how to generate log-normal realisations of the density field by themselves.

C. The student will then apply weighting schemes employed in previous cosmological analyses to correct the contaminated simulation data.

D. The student will then measure how this impacts the inferred correlation of matter and galaxy density and whether these changes can be captured within existing parameterisations of the galaxy-matter relation.
Skills required:
- Knowledge of (or preparedness to learn) programming in either C++ or Python.

Essential references:
A technique the student may employ to mitigate variations of observing conditions in galaxy density data is described in https://arxiv.org/abs/1708.01536 . Similar problems as well as the occurrence of fibre collisions in spectroscopic surveys are discussed in https://arxiv.org/abs/1705.04718 .

A formalism of describing the relation between matter and galaxy density (in projections on the sky) is described in https://arxiv.org/abs/1710.05162 - see especially section IV.C in that paper.

References for further reading:
A tool for generating log-normal realisations of the cosmic density field is described in https://arxiv.org/abs/1602.08503 .

The Buzzard N-body simulations are described in https://arxiv.org/abs/1901.02401 .


Early work on galaxy counts-in-cells statistics can be found in http://articles.adsabs.harvard.edu/pdf/1995MNRAS.276.1425E .
16. What are the nearby alpha-enhanced super-metal-rich stars?

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Project summary:
There is a population of stars near the Sun whose chemical element ratios suggest they are very old, yet have above Solar overall metallicity, suggestive of relative youth. These are known as hi-α-smr stars. Distances and kinematics for a new nearby sample with high-quality properties and abundances will be derived and investigated to probe the mystery of their origins. The project will use stellar properties and abundances from the newest Gaia-ESO Survey results combined with Gaia data to derive kinematics, and will explore the 6-D correlations between metallicity, space motion, age, and α-abundances. This will be the first exploration of this new high-quality data set.

Project description:
A sample of some 2,000 nearby Sun-like stars, selected to include all possible ages and metallicities, has been observed at high-resolution and signal-noise as part of the Gaia-ESO Survey. Accurate astrophysical parameters and chemical elemental abundances will be available for these stars at the start of the project. Gaia DR2 astrometric data is also available. In combination accurate 3-D kinematics can be derived, and ages for many of the stars. The project will analyse the kinematic properties of the sample as a joint function of [α/Fe], [Fe/H] and age where available. Particular care will be taken over the transition from below [Fe/H]=0, where stars in principle may have been formed locally, and above [Fe/H]=0, where the stars must have formed in the inner Galaxy and migrated out to their present locations.

A question of interest is whether or not these stars are the metal-rich tail of the thick disk. If so, then star formation in the early Galaxy extended for surprisingly long and to surprisingly high enrichment levels. If not, where and when might they have formed?

Background:
Chemical elements – known as “alpha” elements - formed in Type II supernovae, whose parent star is massive and short lived, are formed abundantly during the first onset of star formation in a forming Galaxy. Type Ia supernovae create the “iron-peak” elements on a time-scale of typically 1Gyr and longer. The ratio of alpha to iron-peak elements thus is a clock for early Galactic evolution. The “alpha” elements – Ti, Si, Mg, O – are indeed seen to be relatively overabundant in the oldest stars, those formed very early in Galactic evolution. Such stars locally form the Galactic thick disk, and are mostly seen with -1.3<[Fe/H]<-0.3. There is however a population of stars with mild alpha-enhancement and above Solar metallicity in the Solar neighbourhood. Are these the most chemically enriched stars formed very early in Galactic evolution, before the major merger which created the thick disk and initiated growth of the thin disk? In which case early chemical enrichment surprisingly proceeded to well above Solar metallicity. Or are they something else?

We will investigate the kinematics, ages and chemical element distributions of a new high-quality stellar sample designed to address questions of this type.

Project details:
The project work-plan is clearly defined. There is background reading to become familiar with current knowledge of the evolution of the early Milky Way. This story has been re-written in considerable detail over the last two years, based on results from Gaia and the
several large spectroscopic stellar surveys. The combination of precise chemical element
and accurate 3-D kinematics now available shows that the early Milky Way formed stars
fairly rapidly, and evolved chemically in a quite smooth and well-mixed way, over a time of
perhaps 2-3Gyr. The stars formed during this time are alpha-enhanced, with a clear
evolution to declining alpha-over-abundance and increasing iron enrichment up to a level
of about [Fe/H]=-0.2 (see figure below). After this a major merger disrupted the proto-
Galaxy, moving all existing stars into what is today the thick disk, and adding sufficient
new hydrogen to lower the chemical abundance to [Fe/H]=-0.6, and to form a new thin
disk. The merger remnant stars today form the inner Galactic halo. The thin disk has
formed stars and enriched since then. Stars of above Solar metallicity must have formed
in the inner Galaxy and have migrated to the Solar Neighbourhood.
In that context the hi-α-smr stars are a puzzle. They do not have properties representative
of the whole inner thin disk, and are more iron-rich than normal thick disk stars.
The work here is to analyse the (tabulated) abundances for the special Gaia-ESO sample,
and to add 3-D kinematics and where feasible age data from a cross-match to Gaia DR2
and isochrone fitting. Comparison of the Gaia-ESO results with other precision surveys
(most are from planet-search projects) will provide a sanity check on calibration scales.
The Gaia distances can be rederived, and compared with those available from Bayesian
modelling methods (Sanders and Das). 3-D kinematics can then be derived. Statistical
testing will be applied to test for any correlations of chemistry, kinematics and any other
astrophysical property.
The main work is data management, statistical testing and plotting.

The figure below is from a Gaia-ESO paper, Casali etal arXiv:1907.07350. This shows the
history of the Galaxy. The hi-α-smr stars are the red(old) points just above the green
sequence above solar metallicity.

This figure shows [alpha/Fe] (vertical axis) vs [Fe/H] (horizontal axis) for large stellar
samples from the Gaia-ESO and APOGEE surveys.
Metallicity distribution of the Gaia-ESO local precision sample, which will be analysed in the project.

Skills required:
Computing skills to fit isochrones, query data sets, calculate space motions from proper motions, plot data. There are Python scripts available to do most of these.

Useful references:
Casali et al arXiv: 1907.07350
Delgado Mena et al 2019 A&A 624 A78 (hi-precision HARPS sample)
Nissen et al 2017 A&A 608 A112 a classic study
Das, P, Sanders, J 2019 MNRAS 484 294 – a Bayesian ML tool for red giant age/distance
Sanders & Das 2018 MNRAS 481 4093. Isochrone ages from Gaia DR2 data.
General references:
Galaxy merger from Gaia data
Belokurov et al arXiv1802.03414
Helmi et al arXiv 1806.06038
Gallart et al arXiv 1901.02900
17. Realistic Synthetic Saturated Stars

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Supervisor II: Leigh C. Smith, H33, lsmith@ast.cam.ac.uk
UTO: Wyn Evans

Project summary:
The ultimate goal of the project is to produce a machine learning algorithm that will be able to generate realistic synthetic images of a starfield, including saturated stars. The latter present a particular challenge for all current available flux measuring codes, and so being able to generate realistic synthetic saturated stars given defined inputs is the first step to improving these codes.

Project description:
For a great deal of astronomical research, a good estimation of the flux of a source is required. These measurements fall under the wide umbrella of photometry. The most common techniques rely on either integrating the measured signal over a predefined aperture centred on the object of interest or fitting the flux profile of this object to some sort of function, normally chosen from a predefined family.

The above techniques deal poorly with saturated stars. The response to incoming light of most detectors is linear only within a given range. For stars that exceed this range over the exposure time the recovered flux then flattens out to an arbitrary, detector defined value, colloquially known as saturation. Naturally, this means that the fluxes and positions will be extremely poorly measured. If the star is bright enough, the effects of saturation show also in second order effects, like diffraction spikes, that may affect neighbouring objects (Fig. 1).

As a first step in order to develop algorithms that deal with these effects, we need to be able to generate realistic images of saturated stars. The actual appearance of these stars on a real image is mediated by many factors, like the atmospheric observing conditions, the rotation angle of the telescope, etc. This complicates the modelling of these stars.

One way to circumvent these difficulties is through neural networks or other machine learning methods. These could be trained over an ample set of real observations of saturated stars, with well-known fluxes and positions, and under very different observing conditions.

Background:
The field of photometry is ripe for a big update in the techniques used. The most common algorithms and suites, like DAOPHOT, DOPHOT or SExtractor are several decades old. In this time, machine learning methods have erupted in the field, but are yet to be applied to photometry as a general use tool.

Usual machine learning methods, like adversarial neural networks require a generative model that can produce on demand realistic images of saturated stars from a known set of parameters, that then can be compared with the recovered measurements. Such a tool is
lacking at the moment, and this project is a first step in this direction – using supervised machine learning to train a deep neural network to perform this task (see general references below).

**Project details:**
For this project the student will use imaging data from VISTA [1], 2MASS [2] and Gaia [3]. All the data are already available. The project will be staged in three phases:
1. Select and extract from wide field images a suitable training set of saturated stars.
2. Generate a test set of images that can be used to fool traditional photometry algorithms, and then compare the results to the behaviour of these algorithms with actual images to evaluate the effectiveness of the machine learning algorithm.

![Fig. 1: Near infrared image of Westerlund 1 taken by VISTA in which the effects of saturation, black patches in the central region and diffraction spikes around very bright objects, are obvious.](image)

**Skills required:**
Some experience with Python programming is mandatory. Familiarity with machine learning is desirable. Some knowledge of astronomical observing a plus.

**Useful references:**
This project will use data from these facilities:
2. https://irsa.ipac.caltech.edu/Missions/2mass.html

General references:

### 18. Future Constraints on Early Dark Energy Models

**Supervisor I:** Steven Gratton (K07, stg20@cam.ac.uk)  
**Supervisor II:** George Efstathiou (K15, gpe@ast.cam.ac.uk)  
**UTO:** George Efstathiou

#### Project summary:
There are apparent tensions between local measurements of the Hubble parameter and that implied by fits of the standard lambda-cold-dark-matter (LCDM) model to cosmic microwave background (CMB) data. A potential physical resolution of this tension adds a form of “early dark energy” to the Universe, which changes the expansion rate around recombination. Such models are tolerated if not favoured by current CMB data from the Planck satellite. The goal of this project is to investigate how well these models might be constrained by CMB data from the next generation “Simons Observatory” (SO) experiment.

#### Project description:
This is a mathematically demanding project, in which students will learn about current cosmological models, CMB and other data, methods for the computation of predictions of models, and methods for predicting constraints on models from future data sets.

#### Background:
LCDM is a very simple yet very successful model of the Universe. Indeed, the Planck CMB data shows no real preference for any extensions of LCDM.

However, a LCDM model fitted to Planck is in tension with Hubble parameter measurements. While systematic issues with the observations might eventually be found that explain the discrepancy, it is of current interest to consider extensions of LCDM that are tolerated with Planck but also fit the local measurements.

A way to potentially achieve this is to lower the sound horizon at photon-baryon decoupling by of order 10%. “Early dark energy”, behaving like a cosmological constant at early times and then quickly decaying away, can possibly be tuned to do this. The idea is for this contribution to suitably increase the expansion rate of the Universe just prior to decoupling, but otherwise not to have too much effect on cosmology in order not to overly affect predictions for the CMB away from those for LCDM.

#### Project details:
The student will:
- Learn about current cosmological models
- Learn about cosmological constraints from Planck
- Learn about local measurements of the Hubble parameter
- Investigate early dark energy models of the Universe (e.g. arXiv:1904.01016)
- Find out about the Simons Observatory
- Implement early dark energy models in the CAMB code (see http://camb.info)
- Make forecasts about how well the Simons Observatory will constrain such models

This plot, from the Planck 2018 parameters paper, illustrates how well LCDM fits current CMB data. Models that also fit local measurements do not typically fit Planck any better; this project will investigate whether such models will be differentiated by future CMB data.

**Skills required:**

This will be a mathematically demanding project and would suit students intending to take the theoretical cosmology course.

Python will be important for the exploratory aspects of the project, and an ability to read and edit c/fortran code will be needed to implement early dark energy into existing codes.

**Useful references:**

Rock 'n' Roll Solutions to the Hubble Tension, arXiv:1904.01016

**General references:**

A 2.4% Determination of the Local Value of the Hubble Constant, arXiv:1604.01424
Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209
19. Probing QSOs with opacity fluctuations in the helium Lyman-alpha forest

Supervisor I: Martin Haehnelt (K27, haehnelt@ast.cam.ac.uk)
Supervisor II: Prakash Gaikwad (K18, pgaikwad@ast.cam.ac.uk)
UTO: Martin Haehnelt

Project summary:
Similar to the hydrogen Lyman-alpha forest the absorption spectra of QSO show a helium Lyman-alpha forest at four times shorter wavelength. The helium Lyman-alpha opacity and its scatter increase rapidly at z>2.7. This is believed to be due to the inhomogeneous reionization of He II by QSOs reaching completion at z~3. The aim of the project is to model this with the help of the Sherwood suite of cosmological hydro-dynamical simulations and an excursion-set model for the inhomogeneous reionization of He II.

Background:
Studies of the microwave sky together with studies of the Lyα forest in QSO absorption spectra and the Lyman-alpha emission of high-redshift galaxies have told us that the reionization of hydrogen occurred (probably in an extended fashion) between z ∼ 15 and z ∼ 6, while helium was reionized at z ∼ 5 − 3 (see Meiksin 2009 for a review). The hydrogen in the Universe has probably been reionized by the UV radiation of massive stars in high-redshift galaxies. The higher energies required for the ionization of He II mean that accretion onto supermassive black holes in QSOs is the obvious candidate for the reionization of He II. This process will start with individual He III Strömgren spheres around QSOs that will eventually overlap as the volume filling factor of He III regions increases. This process will leave an imprint in the He II Lyman-alpha forest of distant QSOs and modeling this can provide constraints on the evolution of the QSO luminosity function as well as the duty cycle and angular distribution of their UV emission.
Project details:

Left: Projection of the gas density in the Sherwood hydro-dynamical simulation of the Intergalactic Medium (Bolton et al. 2017, https://www.nottingham.ac.uk/astronomy/sherwood/). Neutral hydrogen that traces the web-like distribution of gas is responsible for the absorption lines observed in the Lyman-alpha forest. This is illustrated by the horizontal dotted line, which marks the location of the line of sight corresponding to the Lyman-alpha absorption spectrum shown in green.

Right: Effective optical depths for the corresponding HeII Lyman-alpha absorption as a function of redshift from Puchwein et al. (2015).

Cosmological simulations from the Sherwood simulations suite will provide the necessary physical properties to calculate realistic mock HeII absorption spectra. An excursion set code will thereby be used to model the progression of the overlap of HeII regions for a range of assumptions for the evolution of the QSO luminosity function. The evolution of the HeII opacity in the mock absorption spectra will be compared to that in observed spectra as obtained from the literature.

The project will involve,

- writing your own code to create mock absorption spectra from hydro-dynamical simulations,
- extracting the relevant physical properties from existing cosmological hydro-simulations from the Sherwood simulation suite
- adapting an existing excursion set code for the modelling of HII regions to the modelling of the overlap of HeIII regions,
- post-processing of the hydro-dynamical simulations with the adapted excursion set code.
Skills required:

The project will require programming in Python. Knowledge of C would be beneficial. Knowledge of the curriculum of the Part II course “Introduction to Cosmology” (or equivalent) is desirable.

Project-specific references:

The Sherwood simulation suite: overview and data comparisons with the Lyman-alpha forest at redshifts 2<z<5

Inside-out or outside-in: the topology of reionization in the photon-starved regime suggested by Lyman-alpha forest data

The photoheating of the intergalactic medium in synthesis models of the UV background

Early and Extended Helium Reionization over More Than 600 Million Years of Cosmic Time

General references:

Mo, van den Bosch, and White (Galaxy Formation and Evolution, Cambridge: Cambridge University Press, 2010) give a comprehensive overview of cosmological structure formation and physics of galaxies and the intergalactic medium.

See Meiksin (2009, Rev. Mod. Phys., 81, 1405) for a review of what we know about the intergalactic medium.
# Hot-Dust Poor Quasars in the Sloan Digital Sky Survey

**Supervisor I:** Paul Hewett (Office: H19, Email: phewett@ast.cam.ac.uk)

**Supervisor II:**

**UTO:** Paul Hewett

## Project summary:

The main aim of this project is to determine whether or not the Sloan Digital Sky Survey (SDSS) quasar selection is biased against quasars which show unusually weak emission from hot dust (so-called ‘Hot-Dust Poor’ or HDP quasars). The latest data release from SDSS contains more than 500,000 quasars which were selected for spectroscopic follow-up using a variety of different selection criteria. However, the “core” selection algorithm contains an infrared to optical colour cut, which rejects candidates with weak infrared emission (where the hot dust emission dominates) relative to their optical continuum. HDP objects could make up a significant fraction (20 per cent) of the quasar population – are they missing from the SDSS catalogue?

## Project description:

The work will involve using photometry from the Sloan Digital Sky Survey (SDSS) and infrared surveys (UKIDSS, WISE) to explore the ratio of the hot dust emission (which peaks in the near-infrared) to the emission from the accretion disc (which is dominant at ultraviolet/optical wavelengths) in large numbers of SDSS quasars. The student will investigate if the current SDSS quasar selection algorithm is biased against objects with weak hot dust emission, by exploring the hot dust properties of subsamples of quasars which were selected with different SDSS selection algorithms.

## Background:

Quasars are luminous active galactic nuclei (AGN), where the light emitted from material accreting onto the central supermassive black hole (SMBH) outshines the host galaxy. Understanding how quasars interact with their host galaxies is crucial to developing an understanding of how the most massive galaxies in today's universe evolved in such a way to produce the observed galaxy-SMBH correlations.

Luminous quasars have some fraction of their continuum emission absorbed and re-radiated by hot dust, where the temperature of the dust is maintained by the irradiation from the continuum source. This hot dust may be entrained in a polar wind (e.g. Asmus 2019) which could in turn be accelerated to large radii and “feed back” large amounts of energy into the interstellar medium of the host galaxy.

Some fraction of quasars display little emission from hot dust, but this fraction is poorly determined and appears to increase with redshift, suggesting that dust poorness may be closely linked to the cosmic evolution of quasars. Dust-poor quasars appear to have lower black hole masses and higher accretion rates, suggesting that they may be a transient phase of rapid black hole growth. Understanding the true fraction of Hot-Dust Poor quasars would therefore be a step towards understanding the life cycle of SMBHs.

## Project details:

Cross-matched photometry from UKIDSS and WISE exists for >100,000 quasars from the SDSS DR14Q catalogue. The student will use this data to explore the hot dust properties...
of these quasars, initially using the optical/infrared slopes method of Hao et al. (2010), although there is scope to explore other parametrisations of the hot dust emission. Hao et al. claim that around 20 per cent of quasars at redshifts \( z > 2 \) show unusually weak hot dust emission. However, the main quasar selection algorithm for the most recent incarnation of the SDSS quasar catalogue (the “core” eBOSS selection) makes use of an optical—infra red colour cut, which potentially biases the selection against such Hot-Dust Poor (HDP) objects.

By comparing the HDP fraction in SDSS quasars identified with different selection algorithms, the primary task of the student will be to determine whether or not the core eBOSS selection does indeed bias against selecting such objects. If it does, then the student should be able to quantify the number of HDP quasars which might have been missed by SDSS, which could in turn help improve quasar selection algorithms for future surveys. If however, the SDSS catalogue is already complete in terms of the fraction of HDP quasars which have been identified, then the student will be able to find better constraints on the Hot-Dust Poor fraction and explore how this fraction varies across cosmic time and with physical properties of the quasars.

Figure 1. Composite Spectral Energy Distribution of HDP (downward-pointing triangles) and all (circles) quasars from Jun & Im (2013). The 0.1-1.0\(\mu\)m wavelength region is dominated by emission from the accretion disc, while the 1-3\(\mu\)m region is dominated by emission from hot dust. HDP quasars show unusually weak emission from hot dust.

**Skills required:**

The project is primarily observational in nature and involves an engagement with, and understanding of, large quantities of photometric data. The student will learn to manipulate large observational datasets with e.g. Python/Astropy, Matlab, or TOPCAT – previous experience of any of Python or Matlab would be a distinct advantage.

**Useful references:**

Hao et al. (2010) ApJL 724, L59 - Hot-Dust Poor Type 1 Active Galactic Nuclei
### 21. Quasar host galaxies, star-formation, absorption & starlight

**Supervisor I:** Paul Hewett (Room H19, phewett@ast.cam.ac.uk)
**Supervisor II:**
**UTO:** Paul Hewett

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<td>Notwithstanding the existence of very large samples of luminous quasars, knowledge of the properties of their host galaxies remains limited. The Sloan Digital Sky Survey (SDSS) provides spectra of hundreds of thousands of quasars in which it is now possible to search for the signatures of host galaxies and other galaxies in the local environment of the quasars.</td>
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<td>The project will involve working with large numbers of quasar spectra from the SDSS Data Release 14 (DR14). An observational/data-focussed project by nature. Quantifying the statistical relation between star-formation signatures and the kinematics of the absorption as a function of quasar physical properties (e.g. luminosity, black-hole mass) can provide insight into the physical connection between host-galaxy and quasar evolution.</td>
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<td>Much research into galaxy evolution focusses on gaining an understanding of the tight correlation between the mass of a galaxy and the mass of the central supermassive black hole. It is generally believed that some form of “feedback” connection links the growth of the black hole and star-formation in the host galaxy. Energetically such a scheme is certainly viable but how exactly the galaxy and black hole are linked and, specifically, how the black hole can influence conditions on very large spatial scales within the galaxy remains a key goal of research. The project work will thus fit quite directly into a major area of research attempting to understand the physical link between quasar, host galaxy and outflows.</td>
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<td>The work will involve the use of large numbers of optical spectra of quasars from the Sloan Digital Sky Survey (SDSS) DR7 and DR14 data releases. Catalogues of low-ionisation absorbers due to singly ionised magnesium (MgIIλλ2796,2803) in gas associated with host galaxies, or outflowing material from the quasar, are available for the DR7 and DR14 quasars. Searches for emission from singly ionised oxygen ([OII]λ3728) have been undertaken but further work quantifying the significance of low signal-to-noise ratio emission is desirable. Photometry in the SDSS optical (ugriz), near-infrared (JHK) from the UKIDSS and VHS surveys and mid-infrared (W1W2) passbands is also available.</td>
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Previous work has shown a link between the presence of MgII absorbers and gas ionised by hot stars (Shen & Menard 2012), indicating the host galaxies are currently forming stars. A specific task will be to compare the relationship between absorption and star-formation signatures in the quasar hosts, to that evident in absorber systems present in the quasar environment (likely companion galaxies).

Rather little work has been undertaken trying to identify the presence of starlight from host galaxies but techniques capable of measuring the presence of stellar photospheric emission in the quasar spectra are now available. More can also be done in relating the velocity (relative to the quasar) and physical conditions of outflowing gas to the properties of both quasars and host galaxies, thereby constraining the origin and physical location of the outflowing material.
Figure 1: composite quasar spectra from SDSS DR14. Blue shows quasars with no detectable MgII absorption. Red shows quasars with MgII absorption. The black curve shows the ratio (moved down for clarity). Note the increased strength of the [OII]$_{\lambda 3728}$ emission – more star formation – and the redder spectrum slope – more dust – in the absorber composite.

The majority of the observational data is already available and the project is quite different from one where a new observational data set will be reduced that may enable some model or hypothesis to be straightforwardly tested. Rather, considerable care will be required in understanding the strengths (and limitations) of the information available and then developing schemes for defining and comparing the properties of subsets of quasars while allowing for a number of seemingly subtle, but nonetheless important, selection effects.

Skills required:
The student will need to be comfortable with an exploratory “population” or “statistical” approach to a research problem. There is considerable flexibility in what exactly is investigated and therefore what type of computing skills are most helpful but the ability to code in Matlab or python will be necessary. There will naturally be a degree of background reading and familiarisation with astrophysical properties and analysis techniques but no specific lecture courses are prerequisites.

Useful references:
Paris et al., 2018 A&A 613 51 – the SDSS DR14 quasar catalogue description
Shen & Menard, 2012 ApJ 748 131 – study of the connection between MgII absorbers and star-formation in host galaxies via their [OII] emission.
Joshi et al. 2017 MNRAS 471 1910 – quantifies the [OII]-emission star-formation for absorbing systems that are not directly associated with quasars, important reference/control information.
22. White Dwarfs and the Zwicky Transient Facility

Supervisor I: Simon Hodgkin (Room H39, sth@ast.cam.ac.uk)
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UTO: Mark Wyatt (Room H38, wyatt@ast.cam.ac.uk), Vasily Belokurov (Room H20, vasily@ast.cam.ac.uk)

Project summary:
This project entails a search for eclipses in the lightcurves of White Dwarf (WD) stars by combining data from the Zwicky Transient Facility, with a WD catalogue from the ESA Gaia mission. The systems will be investigated to search for (1) ultra-compact short period eclipsing binary systems, and/or (2) transiting disrupted planetesimals.

Project description:
Background:
White Dwarf stars represent the final stages in the lives of nearly all main sequence stars. Although intrinsically faint, their tiny size, and relatively high mass makes them excellent probes of some extreme physics in the time domain.

A least half of all stars are born as part of a binary (or higher order) system, and thus WDs should show similar multiplicity. WDs in binaries can show dramatic behaviour – the shortest period systems will be very strong sources of gravitational waves, e.g. ZTF J153932.16+502738.8 has a period of <7 minutes (Burdge et al. 2019, see Figure 1). And some, such as the enigmatic AM CVn systems (Ramsay et al. 2018) can be discovered via accretion-related outbursts, and their unusual spectra (Helium-rich, Hydrogen-poor. At present we know of fewer than 50 ultra-compact binaries, and only a few have periods <10 minutes. Thus predictions of the WD merger rate, and their contribution to the associated supernova rate remains poorly constrained. Finding eclipsing double-degenerate systems (e.g. Gaia14aae, Campbell et al. 2015) also enables us to measure their masses and radii, to constrain stellar evolution, and investigate whether they really are viable as progenitors of thermonuclear supernovae.

We now know that most stars have planetary systems, so we might expect WDs to show the remnants of these planets. About 30% of WDs show evidence for atmospheres polluted by metals, and a fraction of these show a significant infrared excess arising from dusty material. But to date, we have only seen direct evidence for the process of planetesimal disruption and subsequent accretion onto the WD in two objects. In WD1145+017 (Vanderburg et al. 2015), transits from disintegrating planetesimals were observed with the Kepler spacecraft. And most recently, an initial investigation of the ZTF transient stream has uncovered a new candidate transiting system (ZTFJ013906.17+524536.89: Vanderbosch et al. 2019). ZTF goes much fainter than Kepler, and thus will allow us to probe a much larger sample of WD stars than was previously possible. This is important, because with only two detections we can’t set constraints on how common the WD1145/J0139 geometry is. A thorough search within the ZTF dataset should
allow us to put strong constraints on the occurrence rate of White Dwarfs with orbiting planetesimals.

Project details:

Time Domain Astronomy is coming of age, and informs the latest generations of space-and ground-based surveys, e.g. ESA’s Gaia mission, the Zwicky Transient Facility (ZTF, Belm et al. 2019), and the Large Synoptic Survey Telescope (LSST).

ZTF is a northern-sky synoptic survey with the 48-inch Telescope at Palomar Observatory, California. The first data release spans almost 300 days, using blue and red filters, with an average cadence of about 3. The full catalogue and lightcurve dataset have been ingested into a local database at the IoA.

Fusillo et al. 2018 used Gaia’s 2nd data release (GDR2) to construct the largest catalogue of WDs ever produced (about 250,000). This new catalogue has also been ingested into the same IoA database.

By combining the Gaia sample of White Dwarfs with the high cadence ZTF lightcurves, you will perform the largest variability study of White Dwarfs to date. Specifically, you will:

1. Extract lightcurves for all WDs in the ZTF data.
2. Explore the quality of the lightcurves.
3. Search for periodic eclipsing white dwarf binaries.
4. Look for irregular eclipses in WD lightcurves arising from the accretion of rocky debris.
5. You may also search for other transient or periodic signals, e.g. associated with accreting or pulsating WDs.

One scientific outcome could be an improved measurement of the period distribution for ultra-compact binary systems. Another could be constraints on the stochasticity of planetesimal accretion and the geometry of the disk created in the process.
Skills required:

Programming, preferably in Python
Familiarity with databases (PostgreSQL) an advantage
Comfortable working with large datasets

Figure 1: (top) Artist’s impression of a pair of closely orbiting white dwarfs [credit ZTF news]¹, (bottom) Lightcurve of ZTF J1539 from Burdge et al. (2019)

² The binned CHIMERA g’ lightcurve of ZTF J1539 + 5027, phase-folded on the 6.91-min orbital period. At phase 0, the lightcurve exhibits a deep primary eclipse, indicating that the hot primary star is producing most of the observed light. Outside the eclipse, there is a quasi-sinusoidal modulation because the primary star heavily irradiates one side of its companion. At phases ±0.5, the secondary eclipse occurs as the hot primary transits the irradiated face of its companion. The phase-folded ZTF g'-band photometry of the object. We were able to discover the object because of its periodic behaviour. c A binned g’ lightcurve obtained with KPED, phase-folded on the orbital period. Error bars are 1σ intervals.

¹ https://www.ztf.caltech.edu/news/ztf-found-shortest-period-eclipsing-binary
Useful references:


23. Magnetohydrodynamical simulations of supernovae with cosmic rays

Supervisor I: Sergio Martin-Alvarez (K18, smartin@ast.cam.ac.uk)

Supervisor II: Debora Sijacki (K17, deboras@ast.cam.ac.uk)

UTO: Debora Sijacki (K17, deboras@ast.cam.ac.uk)

Project Summary: The classical Sedov-Taylor solution to the blast wave evolution of exploding supernovae does not account for the contribution from the cosmic rays produced during the explosion. These cosmic rays constitute a potentially important energy reservoir contained behind the shock and will likely alter the time evolution of these energetic events. By means of the newly developed version of the magnetohydrodynamical code RAMSES including cosmic rays, the student will perform their own magnetohydrodynamical simulations of supernova explosions with cosmic rays and use them to investigate how cosmic rays boost the final momentum of supernova ejecta.

Project Description: The aim of this project is to investigate how including cosmic rays and magnetic fields during supernova (SN) explosions alters the resulting momentum and energy budget in the remnant shell and the contained hot gas bubble. With this aim, the student will be provided with initial conditions for modelling SN explosions and with various versions of code to run the simulations, with and without magnetic fields and cosmic rays. The student will generate simulations with different configurations for these two latter components and analyse the results to explore e.g. the contribution by each type to the momentum of the expanding shell as well as the amount of post-shock turbulence, and the magnetic pressure. This will allow the student to uncover what is the contribution of cosmic rays (and magnetic fields) to the evolution of SN blast waves, how different configurations compare with observations via mock radio images, and thus to better understand how SN explosions shape the interstellar medium of galaxies.

Background: It is believed that massive stars (those with $M > 8 M_\odot$) end their life as supernovae (McKee & Ostriker, 2007). An example of a supernova is the SN1006 remnant, presented by the multi-wavelength observation in the left panel of the accompanying Figure. SNe are one of the most energetic known phenomena in astrophysics, capable of shaping entire galaxies (Somerville & Davé, 2015; Girichidis et al. 2016) by regulating their star formation (Hopkins et al. 2014) and stirring up the different phases of the interstellar medium (ISM; Ceverino & Klypin, 2009). SNe are at a key interface between the nucleosynthesis, stellar evolution and galactic evolution of galaxies.
between stellar evolution and galaxy formation astrophysics. The mechanism behind the explosion of supernovae is far from being fully understood yet, but the amount of energy released in such events is relatively well constrained ($\sim 10^{51}$ erg; Woosley et al. 2002). SN explosions accelerate atomic nuclei and electrons to relativistic speeds (Blandford & Ostriker, 1978). These particles constitute cosmic rays and accumulate a non-negligible amount of the energy of a SN. Due to their relativistic behaviour and large free-streaming lengths, cosmic rays undergo lower energy losses during blast wave expansion and have the potential to re-accelerate the explosion ejecta, boosting its momentum and increasing the impact on the ISM surroundings (Kim & Ostriker, 2015; Diesing & Damiano, 2018). As a result, understanding how cosmic rays influence SN explosions remains an unsolved problem in ISM and galaxy formation astrophysics. Another frequently neglected component are magnetic fields, due to their modelling complexity. Whether magnetic fields boost the momentum of SNe or hamper their growth by draping expanding bubbles is not known yet. Similarly, the observed structure of the magnetic field in supernova remnants (SNR) is not properly understood (Byung-il & Norman, 1996).

Only now, in the advent of numerical codes capable of modelling cosmic rays and the magnetic fields that regulate their propagation self-consistently, we can finally investigate how cosmic rays impact SNR evolution. The student leading this project will do so by making use of the recent extension of the well-known RAMSES code (Teyssier, 2002) to model cosmic rays (Dubois & Commerçon, 2016). A projected image of an isolated SN simulation ran with RAMSES is shown in the right panel inset of the accompanying Figure. Pursuing this research will lead to a better understanding of SN explosions and which physics are required for theoretical models to accurately reproduce the SNRs observed in our galaxy.

**Project details:** This project is based on performing and analysing numerical magnetohydrodynamical simulations. For this, the student will be provided with initial conditions for the problem at hand and three versions of the RAMSES code to be used (hydrodynamical, magnetohydrodynamical or MHD, and MHD + cosmic rays).

1. As a first step, the student will revise the relevant literature and review the analytic solution of a Sedov-Taylor blast wave. This will serve as a basis to compare with the general theory the simulations performed by the student.
2. The student will familiarise themselves with operating on HPC environments and running massively parallel simulations. The first simulations will be followed by the generation of projected maps and animations (videos) of the explosion. Some example codes will be provided for this. The student will continue by commencing to explore quantities of interest for the project such as the evolution of the momentum of the SN shell.
3. The student will produce the main set of simulations, exploring the parameter space of cosmic rays and magnetic fields, such as B field topology, cosmic rays’ diffusion and streaming efficiencies and the fraction of initial SN energy stored in the cosmic ray component. At least 10 different runs should be performed with the possibility of expanding the scope of the project if there is time available.
4. The student will study how the inclusion of magnetic fields and cosmic rays alters the properties of SN and SNRs, including their final size, their energy budget and energy fraction per component, whether shell instabilities are demoted by magnetic fields, etc.
5. **Extra:** For those students with good computational skills and with an aim to do additional work, various possible extensions exist:
   a. The student could do a direct comparison with SN observations by generating mock optical and synchrotron observations of their simulations (software provided by supervisors), addressing the debate about what is the structure of the magnetic field in the rim of SNRs and reviewing whether state-of-the-art full MHD+CR simulations can explain the origin of radial magnetic fields inferred from synchrotron observations (see e.g. West et al. 2017).
b. The environment where SN events take place is known to alter the amount of momentum that the explosion deposits on the ISM (Gatto et al. 2015). To address this issue, the student could review the same previously studied SN properties using shearing box initial conditions (i.e. a small section of a galactic disk).

**Skills required:** this project has a substantial computational component. Consequently, the student is expected to be comfortable working using a UNIX shell and programming with a scripting language of choice (preferably python). Some familiarity with compiled languages (such as C or Fortran) is preferred to facilitate the analysis. Students are encouraged to discuss any other computational abilities they may have that could be of use for the project e.g. CUDA, MPI/OpenMP protocols, AI frameworks, etc. Students should also be familiar with the Part II ‘Astrophysical fluid dynamics’ course (Clarke & Carswell, 2014), while good knowledge of ‘Structure and evolution of stars’ and ‘Stellar dynamics and structure of galaxies’ is desirable.

**References:**


**Other references:**


**24. Host galaxies and supermassive black holes in X-ray selected active galaxies and quasars**

Supervisor I: Richard McMahon (Hoyle H49, rgm@ast.cam.ac.uk)
Supervisor II: Estelle Pons (Hoyle H55, pons@ast.cam.ac.uk)
UTO: Richard McMahon

**Project summary:**
The goal of this project is to use new high resolution optical imaging observations from the European Space Agency (ESA) Gaia satellite to determine how much of the energy in the optical waveband for a sample of X-ray sources is due to extended starlight and how much is from a compact accreting black supermassive black hole.

**Project description:**
This is an extragalactic observational project. You will learn about a range of different observational datasets primarily from space satellite telescopes, XMM-Newton, Gaia, Hubble Space Telescope, Spitzer and learn how to extract physical information from observations with a range of wavelengths. The primary goal of the project is to determine how Gaia observations can be used to determine the relative contribution of extended emission from starlight from the host galaxy in quasars and from compact emission from a central active nucleus powered by accretion onto a super massive black hole.

**Background:**
Gaia's exceptional spatial resolution (FWHM=0.1 arcsec), corresponding to a physical scale of 0.5-1.0kpc over the redshift range 0.5 to 10.0, provides Hubble Space Telescope image quality over the whole sky and therefore has the potential to resolve the compact nuclear region of over 1 million active galaxies from their more extended host galaxies.

One of the most exciting phenomena in the Universe are supermassive black holes (SMBHs e.g. $10^8$ Solar masses in our own Milky Way and up to $10^{10}$ Solar masses in the most massive galaxies) that inhabit the central regions of all massive galaxies including our own galaxy the Milky Way. Accretion of matter onto these objects results in radiation over a wide range of the electromagnetic spectrum from the infra-red to X-rays. The most luminous of these objects are called quasars where electromagnetic radiation from the accreting supermassive black hole in the central active galactic nucleus (AGN) outshines starlight by a factor of up to 10-10,000. The mass of the black hole appears to correlate with the mass of the stellar bulge in present day galaxies (Kormendy & Ho 2013) which is explained in galaxy formation models by the coeval assembly of stellar bulges and SMBHs through gas-rich mergers that fuel both star formation and black-hole accretion which manifests itself as a luminous quasar phase.

The first part of this project will start with sample of over 5000 X-ray selected sources detected by XMM-Newton (Chen et al., 2018). Gaia optical observations will be used to determine whether Gaia observations can be used to determine which X-ray sources have optical emission which is dominated by emission from a compact point source and which have significant contribution from extended starlight. The Gaia observations will be compared Hubble Space Telescope and ground based observations.

The second part of the project will aim to determine the ratio of the brightness of the central quasar and the host galaxy and investigate how this is correlated with X-ray
luminosity which is primarily from the inner accretion disk region and mid infra-red luminosity which is believed to be produced by hot dust from a surrounding torus.

The observed properties will be correlated with optical, X-ray and infra red luminosity in order to determine how the quasar host galaxy properties are correlated with X-ray activity or thermal emission from irradiated hot dust using observations with the XMM-Newton X-
rya Satellite and infra-red data from the Spitzer satellite. Figure 1 shows an example of a luminous quasar powered by a $10^9$ solar masses super massive black hole.

**Project details:**
The project will use data from the Gaia satellite to investigate what fraction of the optical energy in X-ray selected sources is from a compact stellar nucleus versus the extended host galaxy. The Gaia data will be compared with observational data from the Hubble Space Telescope. If time permits you will include the analysis of mid infra red observations from the Spitzer satellite.

**Skills required:**
- The work is a mixture of observational and computational work and will involve the development of Python software for the analysis of tables of observational data.
- You will also need to visually inspect image taken with the Hubble Space Telescope

**Useful references:**
5. Kormendy and Ho, 2013, ARA&A, 51, 511; Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies

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**Figure 1:** Hubble Space Telescope image of the quasar 3C273 showing the host galaxy.

**Figure 2:** Recent image of supermassive black hole in the galaxy M87
25. Measuring the sizes of ionized hydrogen near zones in high redshift quasars in the epoch of reionisation

Supervisor I: Richard McMahon (Hoyle H49, rgm@ast.cam.ac.uk)
Supervisor II: Estelle Pons (Hoyle H55, pons@ast.cam.ac.uk)
UTO: Richard McMahon

Project summary:
The aim of this project is to measure the sizes of ionized Hydrogen near zones around a sample of around 10 luminous quasars with high redshift (z>6) in the epoch of reionization using new observations. The results will be used to investigate how different ionized Hydrogen near zone size estimators can be used to constrain the neutral hydrogen fraction of the Universe; the clumpiness of the Universe and the ages of quasars in the epoch of reionization 700-800 million years after the Big Bang.

Project description:
This is an observational cosmology project and will introduce you to extragalactic observational astronomy and data analysis. The project will show how observational measurements can be used to determine astrophysical parameters and will investigate the uncertainties in the derived parameters using measurements on simulated observations.

Background:
The `Epoch of Reionization'(EoR) is a fundamental milestone in the history of the Universe. This fundamental phase transition in the Universe when the first luminous ultraviolet sources ionize the neutral predominantly hydrogen intergalactic medium is one of the final frontiers in astrophysics. The Lyman-α forest in bright high-redshift quasars is one of the main probes of this transition (e.g. Becker et al., 2015; see also Figure 1). We have recently discovered a new sample of high redshift quasars that can be used to measure the sizes of Hydrogen ionized near zones around high redshift quasars. These recent observations (Figure 10 from Reed et al, 2017) support a picture where there are significant line of sight variations in the structure of the intergalactic medium and also surprising evidence of small near zones over a wide range of redshifts. Reed et al. found two z ~ 6.2 quasars with H II near zone sizes ≤3 proper Mpc that could indicate that these quasars may be young with ages 10^6–10^7 years or lie in over dense regions of the IGM. The aim of the project is to understand the scatter in the observations and the existence of small near zones which could be indicate that some the quasars are so young <100 million years that the UV radiation has not fully ionized the region around the quasars.

Project details:
1. The project will involve re-analysis of observations of the z=7.1 quasar ULAS J1120+0641 used by Mortlock et al. 2011 and new higher quality observations to measure the hydrogen damping wing and near zone size in Mpc.
2. The analysis will then be repeated for around 6-10 quasars with z>6.5 using new data from the Very Large Telescope in Chile, using a range of different analysis methods to estimate the unabsorbed continuum emission including using synthetic quasar spectra provided by Paul Hewett. Figure 1 shows an example spectrum for a z=6.1 quasar.
3. Analysis will be repeated for simulated absorption spectra generated from numerical simulations of the intergalactic medium from Keating et al, 2015. The simulated data
will be combined with rest frame ultra-violet quasar spectra and analysed over a range of spectral resolutions (100-1000 km/sec).

4. The distribution of near zones sizes versus redshift for the simulated data will be compared with recent observations from Reed et al. 2017 using robust statistical estimators.

Skills required: (Summarise the computing skills that are required to successfully complete the project. Specify any lecture courses required for the project.)

- The work is a mixture of observational and computational work and will involve the development of Python software for automated analysis of observational and simulated data.
- The work will involve modifying existing software and writing new Python computer programs and the use of robust statistical fitting techniques.

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

General references: (List papers referred to in the project description)

![Figure 1: A high signal-to-noise spectrum of the quasar ULAS J1319+0959 at z = 6.13 from Becker et al. (2015), obtained with the X-Shooter spectrograph on the Very Large Telescope (VLT). The spectrum has been rebinned to 1.5 Å per pixel for presentation purposes. This illustrates many of the features reviewed here – see the text in II for a description.](image)

**Figure 1**: Optical spectrum of a high redshift quasar showing redshifted hydrogen Lyman-α (λ_{rest}=121.6nm) emission and absorption signatures including near-zone region.
26. Large refractive and diffractive telescopes for astronomy

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Introduction

Galileo first used a refracting telescope in 1610 and for the next 300 years refracting telescopes were the standard for large telescopes for astronomy. But as astronomers demanded bigger and bigger telescopes, problems with lens sag and non-uniformity of the refractive index of the lens material eventually led to reflecting telescopes being the best design form for apertures greater than about 1m and we are still locked in to this point of view.

But things have changed since the early 20th century. Firstly, we now have space telescopes and lens sag is clearly not a problem in a weightless environment. Secondly, we now know how to make large reflective segmented telescopes (e.g. Keck, JWST and the ELT). This opens up the possibility of having a large segmented refractive telescope because lens sag and refractive index non-uniformity should not be a problem because the individual segments can be smaller than 1m across. Maybe the time has come to look at refracting telescope designs once again. A major advantage of a refracting telescope is that the tolerance on positioning the optics to achieve diffraction limited performance is much better and so they are far easier to align than reflecting telescopes. This is a big advantage for unfolding, self-aligning space telescopes. Furthermore, in recent years, it has become possible to manufacture diffractive optics (ones which use interference from different zones) yet no large telescope has been made using this new technology.

Some related work is already being done. The Nautilus project (arXiv:1906.05079) is a concept for a segmented space telescope made up of 40 unit telescopes with each telescope being ~8m in diameter. The MOIRE project (https://www.ball.com/aerospace/programs/moire) is a space telescope concept for Earth observations (see figure 1).

Project Work

This project involves designing segmented refracting and/or diffracting telescopes using "Zemax opticalstudio" which is a sophisticated software package for designing optical systems. Segmented telescopes are relatively common in the form of large reflecting telescopes but there are no segmented refractors at all. The design work will focus on segmented telescopes including thin lens designs (pseudo-Fresnel lenses) and refractive-diffractive designs.

1. Start with a simple segmented thick lens refracting telescope design. This will introduce the student to the zemax software and in particular how to model segmented designs.
2. Progress to a thin lens design. This will be similar to a Fresnel lens. The important thing to evaluate here is the effect of the large optical path difference between different segments.
3. Add chromatic aberration correction to the thick and thin designs.
4. Evaluate the alignment tolerances of the designs and compare to those of reflective designs.
5. Model diffractive designs.
6. Make hybrid refractive/diffractive designs.
7. Optimise the designs in terms of size and weight (for space applications) by reducing the overall length and using a non-redundant sparse aperture segment pattern.

Although this is a computer-based project, the student does not have to write any code (however the project could be taken to an advanced level by driving Zemax with python scripts). Some knowledge of optics would help but it is not essential.

References

27. X-raying the fuel supply of nearby active galactic nuclei

Supervisor I: Prof. Chris Reynolds (Room H15, csr12@ast.cam.ac.uk)
Supervisor II: Dr. Dom Walton, dwalton@ast.cam.ac.uk
UTO: Prof. Chris Reynolds

Project summary:
How are active galactic nuclei fed? What kind of structures are set up that can feed large amounts of gas from the outer regions of a galaxy down onto the central supermassive black hole? Just how much gas is fed inwards compared to that actually swallowed by the supermassive black hole, i.e., are black holes messy such eaters that they eject the vast majority of incoming gas?

In this project, you will use spectral data from the Chandra X-ray Observatory to address aspects of AGN feeding. You will employ a new data analysis technique to existing observations in NASA’s data archives in order to measure the size and mass of the fuel reservoir around a small sample of nearby active galactic nuclei, thereby addressing the questions posed above. These observations will provide an important underpinning to new theoretical models of galaxy formation/evolution and AGN feedback.

Project description:

Background:

(Left) Artist’s Impression of immediate environment of an AGN. (Right-top) Chandra X-ray spectrum of the Circinus galaxy, one of our targets. Clearly visible are emission lines from cold gas in the vicinity of the AGN. (Right-bottom) Chandra X-ray image of the immediate region about the Circinus galaxy, filtered to show the fluorescing gas.

The spectacular active galactic nuclei (AGN) observed in a few percent of galaxies are powered by the accretion of gas onto supermassive black holes. But how exactly are AGN fuelled? What astrophysical processes drive large amounts of gas down onto the black hole, and why do those processes only operate in a small fraction of galaxies?
Once the gas is in the general vicinity of the supermassive black hole, how does it proceed to lose angular momentum so that it actually be accreted?

To address the fuelling question, we need to gain a clear understanding how much gas there is in the galactic core and how it is distributed. Great strides have recently been made by the Atacama Large Millimetre Array (ALMA) which can map out the cold molecular gas close to AGN, but significantly more gas may be present in hotter phases that do not contain molecules. X-ray astronomy, and particularly the study of X-ray fluorescence emission lines, provides an excellent way of studying these other phases of the AGN fuel supply (Kawamuro et al. 2019; Hitomi Collaboration 2019).

Project details:
The availability of excellent data from the Chandra X-ray Observatory and, importantly, the development of new analysis techniques provides an opportunity to make new, high impact, measurements of the fuel supply in a sample of nearby AGN. In this project, you will conduct a careful analysis of data from Chandra’s High-Energy Transmission Grating (HETG) for six nearby AGN. You will learn how to obtain the data from NASA’s primary data archives, the steps necessary to turn the raw data into “science ready” spectra, and then the methods for analysing and extracting physics from the spectra. You will implement a new analysis technique whereby subtle differences in the shapes/widths of the same emission line seen in different diffraction orders can be used to probe the spatial extent of the emitting gas (Liu et al. 2017; Marshall 2017). As part of this work, you will calibrate this technique using the Chandra simulation software MARX.

From your measurements, you will calculate the total mass of the gas in the galactic core and its dynamical state. Comparing these measurements across your small sample, you will seek correlations between these quantities and other characteristics of the AGN, such as its luminosity or obscuration. These results will pave the way for future studies with next generation X-ray spectrometers such as XRISM and Athena, and will provide crucial input to theoretical models of galaxy formation and evolution.

Skills required:
Prior experience with unix based platforms is highly desirable. Otherwise, no specific computing experience is required.

Useful references:
- Marshall, H., 2017, Chandra Newsletter (http://cxc.harvard.edu/newsletters/)

General references:
### Project summary:

This project focuses on modelling the atmospheres of warm terrestrial planets, in particular, capturing the effect that sulfur species have on their atmospheric photochemistry. The archetypal warm terrestrial planet is in our own solar system, Venus, but successful models of its atmosphere have eluded us for decades. With thousands of exoplanets now discovered, many of which are on short-period orbits and are the easiest to follow up with detailed atmospheric observations over the next decade, it is essential we develop improved models of warm terrestrial planet atmospheres. Improving our understanding of these planets is essential for mapping boundaries of habitability in exoplanet systems and understanding the divergent climatic fates of Earth and Venus. This project will build upon existing photochemical models to extend them to warm terrestrial planets, using Venus as a benchmark.

### Project description:

The goal of this project is to gain a key insight into the atmospheric chemistry of terrestrial planets in a greenhouse state. This will be achieved by studying Venus, as a key natural laboratory for greenhouse worlds, and modelling its full atmospheric chemistry to within an order of magnitude accuracy. The project will build upon an existing 1D photochemical-kinetics model that incorporates C/H/N/O/P/S, and compare the results to Venus. The project then has the scope to extend to exoplanets by replacing the solar spectrum with that of other stars, to investigate the atmospheric properties of Venus-like exoplanets.

### Background:

Earth and Venus are planets with very similar astrophysical parameters (semimajor axis, radius, mass, brightness temperature), but which have had markedly different environmental and geophysical histories: Venus is a greenhouse world, with a massive atmosphere and limited mantle convection; Earth is a geologically active, temperate world, with an atmosphere that nurtures abundant life. Understanding why Earth and Venus are so different is essential for assessing exoplanet habitability. The atmospheric chemistry of Venus is complex, and to date there has been no complete model of Venus's atmosphere. The goal of this project is to produce the first model that reproduces the major structure of Venus's atmospheric chemistry from the surface to upper atmosphere. In this, accuracy will be sacrificed in favour of generality, such that a model is produced capable of describing warm terrestrial planets throughout the galaxy.

### Project details:

The goal is to take an existing atmospheric chemical model for exoplanets, and update the model to reproduce every observationally-constrained chemical profile within Venus's atmosphere to within one order of magnitude, using a network that can also be applied to...
planets with different semimajor axes around different kinds of stars.

The project will have this essential structure:
Step 1: Read background literature and gain familiarity with the two sulfur cycles, the role of chlorine chemistry with these cycles, and mysterious UV absorber that has been inferred to regulate Venus’s sulfur chemistry.

Step 2: Learn to use the ARGO photochemistry/diffusion code with the STAND2020 sulfur network.

Step 3: Consider elemental sulfur nucleation near the surface of Venus, from S and S₂ to S₈, and add the reverse reactions to the network, testing for thermochemical equilibrium. This is critical for constraining the sulfur budget in the lower atmosphere.

Step 4: Test the two sulfur cycles: the SO₂ <-> H₂SO₄ upper atmospheric cycle that removes SO₂ from the upper atmosphere; and OCS <-> S + CO as a carrier of reactive sulfur from the surface through the lower atmosphere. Compare the mechanisms to the listed mechanisms from published papers.

Step 5: Compare the profiles for SO, SO₂, H₂SO₄, S₂, S₃, Cl₂, HCl, OCS, CO, and H₂O to observations. This is the final goal of the project, and qualifies as an important development in Venus atmospheric modelling.

Step 6: If time allows, replace the sun with a different star in the code, and find out how this affects the upper atmospheric chemistry of Venus.

Step 7: If time allows, remove the ‘mysterious absorber’, and find out its impact on the full atmospheric chemistry of a Venus-like exoplanet without this absorber, around the sun and other stars.

Skills required:
The student will benefit from having had previous experience of Python, but broader knowledge of programming languages would be fine. Mathematically, familiarity of differential equations and how to solve them will be important.

Useful references:


Krasnopolsky, V. A. (2013). S3 and S4 abundances and improved chemical kinetic model for the lower atmosphere of Venus, Icarus 225(1): 570-580. *Updated sulfur network that improves the S3 predictions, bringing them better in line with observations.*


*Why should we even bother modelling Venus as an exoplanet? I recommend reading this first!*
### 29. Mapping the lighthouses — Milky Way structure using eclipsing contact binaries

**Supervisor I:** Jason Sanders (H33, jls@ast.cam.ac.uk)

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

**UTO:** Vasily Belokurov

#### Project summary:
Eclipsing contact binaries are numerous and satisfy a very tight period-luminosity relation, making them ideal tracers of the structure of the Milky Way. Large multi-epoch photometric surveys have generated light curves for billions of stars which can be automatically sorted and classified using machine learning approaches. The VVV survey is a multi-epoch near-infrared survey so ideal for extracting variable stars within the highly-extincted central regions of the Galaxy. The project would involve constructing a catalogue of contact eclipsing binaries from VVV and measuring their spatial and kinematic distribution.

#### Background:
In the era of large Milky Way surveys, we are now charting our Galaxy in unprecedented detail. The astrometric mission, Gaia, has measured trigonometric distances to over a billion stars in the Galaxy. However, the accuracy of the trigonometric distances rapidly decays with distance, and for probing the fine structure of more distant parts of the Galaxy, like the Galactic bulge, we instead use standard candles, for instance Cepheids, Red Clump stars or RR Lyrae.

One interesting type of standard candle are eclipsing contact binaries. These form a subset of eclipsing binary stars where the two outer envelopes of the two stars are in direct contact. The archetypal star of this class is W Ursae Majoris (W UMa) so this class is sometimes referred to as EW distinguishing it from detached eclipsing binaries (EB after Beta Lyrae) and semi-detached eclipsing binaries (EA after Algol). In a contact binary the two stars fill their Roche lobes such that their radii and hence density are related to the orbital period. In the near-infrared (which is less sensitive to temperature and metallicity variations), it has been established that EW binaries follow a tight period-luminosity relation (see Fig. 1. and Fig. 3) giving distances to ~7% (Chen et al. 2018). Their light curves (e.g. see Fig. 2) allow EW binaries to be distinguished from other types of variable stars. Additionally, there are early contact binaries and red giant contact binaries that have similar light curves to W UMa type but don’t satisfy as tight a period-luminosity relation (Muraveva et al. 2014).

In recent years, the structure of the Galactic bulge has been characterised using deep infra-red photometric surveys. The barred X-shaped structure (McWilliam & Zoccali 2010) has been mapped out using red clump giant stars. Other tracers give different results on the structure, either due to tracing an intrinsically distinct component or due to larger distance errors. The X-shape has only been seen using red clump stars and its reality has been debated (Lopez-Corredoira et al. 2019). EW binaries could potentially provide another high-quality distance indicator to corroborate and expand upon the results using red clump stars. For instance, Rucinski (1997) demonstrated how the structure of the Galactic bulge could be probed with EW stars. With the reliable period luminosity relations calibrated on Gaia data and large data samples, there is scope for huge developments. The VVV survey is a near-infrared (Ks band) multi-epoch survey of the Galactic bulge and southern Galactic disc. From this survey a catalogue of ~2 billion light curves has been constructed along with astrometric solutions (providing proper motions of the sources). It thus makes it an ideal survey for this task.
Project details:

The project is composed of three stages: developing a classifier to find EWs, characterise their properties and investigate their spatial (and kinematic) distribution.

1. Construct a parent set of existing variable star classifications that overlap between VVV and OGLE, ATLAS, ZTF, ASASSN.
2. Train a machine learning classifier to extract the classified EW light curves from a set of VVV light curve summary statistics.
3. Apply the classifier to all VVV light curves to produce a list of new EWs.
4. Characterise the period and light curve shapes for the new EWs and prune any contaminants (e.g. RR Lyrae).
5. Estimate extinction corrections for these sources using pre-existing extinction maps.
6. Use period-luminosity relations to measure distances to the EWs.
7. Build a model for the spatial distribution of the EWs.
8. Inspect the transverse velocity structure using proper motions from Gaia and VVV.
9. Optional: Combine with larger sample of EWs.
10. Optional: Extend classifier to more classes of variable (e.g. RR Lyrae).
11. Optional: Improve period-luminosity relations using new sample combined with Gaia DR2 (and measure the parallax offset).
12. Optional: Investigate properties of early CBs and red giant CBs.
Skills required:

Programming skills in Python are desirable. Any knowledge of machine-learning techniques, Bayesian inference and SQL queries is desirable.

Useful references:

**Classification of variable stars:**
- Heinze et al. (2018) ATLAS: [https://ui.adsabs.harvard.edu/abs/2018AJ....156..241H/abstract](https://ui.adsabs.harvard.edu/abs/2018AJ....156..241H/abstract)
- Soszynski et al. (2016) OGLE: [https://ui.adsabs.harvard.edu/abs/2016AcA....66..405S/abstract](https://ui.adsabs.harvard.edu/abs/2016AcA....66..405S/abstract)


**Bulge structure with W UMa:** Ruckinski (1997) [http://adsabs.harvard.edu/abs/1997AJ....113..407R](http://adsabs.harvard.edu/abs/1997AJ....113..407R)

**General references:**
**30. The Sausage factory — chemical structure in the Milky Way disc from an early major merger event?**

**Supervisor I:** Jason Sanders (H33, jls@ast.cam.ac.uk)

**Supervisor II:** Vasily Belokurov (vasily@ast.cam.ac.uk), Wyn Evans (nwe@ast.cam.ac.uk)

**UTO:** Vasily Belokurov, Wyn Evans

**Project summary:**
Recent results from the Gaia satellite have demonstrated that the oldest, most metal-poor stars in the Milky Way are composed of two dynamically and chemically distinct types of stars. This is evidence of an early major merger onto the Milky Way where we are observing a combination of stars formed in the Milky Way and in the merging galaxy (referred to as the Gaia Sausage). The merger could have brought significant quantities of gas into the Milky Way, prompting significant star formation and causing a distinct structure in the distribution of chemical elements. The project aim is to construct chemical evolution models of the Milky Way and its merger with the Sausage galaxy to test this theory.

**Background:**
The stellar halo of the Milky Way provides the fossil record of the early formation of our Galaxy. The constituent stars are old, predominantly metal-poor and have hot spheroidal kinematics. The constituent stars either formed within the early Milky Way (in-situ) or were accreted from dwarf galaxies (ex-situ). However, the halo stars retain memory of their origin in their patterns of chemical elements and kinematics (Belokurov et al. 2013).

The chemical evolution of galaxies predicts stars lie along a sequence in [\(\alpha/Fe\)] and [\([Fe/H]\)] (Pagel 1997, see figures) — that is the ratio of alpha elements (such as oxygen, silicon etc.) to iron against the ratio of iron to hydrogen. Two dominant production mechanisms for metals in galaxies are Type Ia and Type II supernovae. Type II supernovae essentially produce equal quantities of \(\alpha\) elements and iron, dominate the early chemical evolution of the galaxy and produce a horizontal sequence in [\(\alpha/Fe\)] against [\([Fe/H]\)]. Eventually (after \(~1\) Gyr) Type Ia begin contributing producing more iron than \(\alpha\) elements and giving rise to a downwards sequence in [\(\alpha/Fe\)] against [\([Fe/H]\)]. The [\([Fe/H]\)] position at which the sequences join reflects the mass of the host galaxy.

Spectroscopic studies of the metal-poor stars (see Nissen & Schuster 2010, Helmi et al. 2018, Mackereth et al. 2019 and Fig. 1) have demonstrated the existence of two distinct sequences in [\(\alpha/Fe\)] against [\([Fe/H]\)], believed to correspond to in-situ and ex-situ stars. In-situ stars follow a horizontal sequence at low metallicity as they were formed before Type Ia supernovae became important, whilst the ex-situ stars at similar metallicity were formed after Type Ia supernovae had contributed significantly to the gas in their host galaxy. The astrometric data from Gaia indicates that the kinematics of the two sequences are distinct (Figs. 1 & 2) supporting the picture of a significant galaxy merger onto the Milky Way \(~10\) Gyr ago — the so-called Sausage (or Gaia Enceladus) galaxy (see Belokurov et al. 2018).

For the more metal-rich stars ([\(Fe/H]\]>\(~0.7\) dex), there is also a bimodality in the chemical space (the so-called thin and thick disc sequences) which has a less clear origin. It is possible that the Milky Way's evolution proceeded along the upper sequence before the Sausage galaxy brought significant quantities of metal-poor gas resetting the Milky Way onto the lower sequence. This matches the observation that the thin disc sequence connects onto the metal-poor accreted ex-situ Sausage sequence. For example, Spitoni et al. (2019) present models (see Fig. 3) of this infall scenario. Spectroscopic stellar data should be able to distinguish between this scenario and other explanations of the disc bimodality.
Project details:

The project consists of two components: producing predictions for the chemical evolution of the Milky Way Galaxy alongside a major merger and comparing these predictions with the latest spectroscopic stellar observations. The student will:

1. Build a simple single-zone chemical evolution model to describe the infalling Sausage Galaxy.
2. Build a multi-zone chemical evolution model for the Milky Way.
3. Use the Sausage model to add accreted gas to the Milky Way model.
4. Investigate the impact of varying parameters of the infall such as the accretion rate and radial distribution.
5. Compile spectroscopic data from APOGEE, GALAH and LAMOST surveys.
6. Compare the models to the data in the [$\alpha$/Fe] and [Fe/H] space.
7. Constrain the time of the merger onto the Milky Way.
8. Optional: Use simulations to investigate the geometry of gas infall in different merger scenarios.
**Skills required:**
Programming skills in Python are desirable. Knowledge of C++ would be useful.

**Useful references:**


*Dynamics of the Sausage:* Belokurov et al. (2018) [http://adsabs.harvard.edu/abs/2018MNRAS.478..611B](http://adsabs.harvard.edu/abs/2018MNRAS.478..611B)

**General references:**

*Stellar halo:* Helmi 2008 [http://adsabs.harvard.edu/abs/2008A%26ARv..15..145H](http://adsabs.harvard.edu/abs/2008A%26ARv..15..145H)

*Galactic Archaeology:* Belokurov 2013 [http://adsabs.harvard.edu/abs/2013NewAR..57..100B](http://adsabs.harvard.edu/abs/2013NewAR..57..100B)

31. The effect of giant planets on protoplanetary disk thermal and chemical structure

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Supervisor II: Mihkel Kama, mkama@ast.cam.ac.uk
UTO: Oliver Shorttle

Project summary:
This project focusses on understanding the influence of giant planets on the thermal and chemical structure of protoplanetary disks. Recent observational and theoretical results, both considering our own solar system and those contained in nearby young clusters, show the profound impact giant planets can have on disk structure: opening gaps in the dust, gas, and perturbing the transport of solids through the disk to create distinct chemical reservoirs. The implications of this for the elemental budget of planetesimals and planets has yet to be fully explored, and developing this link between the disk physical structure and solid/ice composition in the vicinity of giant planets is the aim of this project.

Project description:
This project is a theoretical investigation of how disk properties are perturbed by the formation of giant planets and will be suited to students with an interest in exoplanets, disks, and solar system evolution. It will involve running and improving disk radiative transfer and chemical models, using planet masses and disk theory to modulate properties such as the disk surface density structure and dust properties, and formulating a physical understanding of the model output. This will then be linked with models describing solid/ice compositions in disks and compared with solar system and exoplanet data.

Background:
The total abundance of chemical elements in the sun reflects the composition of the cloud from which our solar system formed. However, planets and asteroids show important deviations from this: Earth and all inner solar system solids are remarkably poor in carbon; some asteroids are water-rich while others are dry; the C/O ratio in many giant exoplanets has been proposed to be non-solar and Jupiter is potentially sub-solar in its H₂O abundance. What causes planets to form compositionally distinct from their host star? This project will investigate how gap opening by planets in disks can affect the composition of what they accrete by heating or cooling nearby solids in the disk.

With thousands of exoplanets now discovered, attention is increasingly shifting to more detailed characterisation of their properties, in particular their composition and what it might tell us about their formation. At the same time, observations of polluted white dwarfs are providing a snapshot of the composition of planetary material at the other end of a system’s life cycle: in the post-main sequence stage of a massive star, as rocky materials spirals onto its white dwarf remnant. It is, therefore, increasingly important to understand what sets the elemental composition of the building blocks of planets.
A potentially key factor in the dynamics of protoplanetary disks is the formation of giant planets. Once they reach a critical mass, they open up gaps in the disk, whereby the majority of dust in the vicinity of the planet’s has been removed. These gaps are associated with pressure maxima just outside the giant planet’s orbit, which then act to trap large dust grains in the outer disk creating a radial chemical segregation within the disk. Ultimately, if the planet grows large enough, a hole in the gas distribution in the disk may also be opened.

The key question from these observations is what effect does gap opening have on the composition of solids and ices in the disk, and thereby the composition of low-mass planets forming nearby?

The aim of this project is to investigate how these major perturbations to disk structure caused by giant planet formation map into the composition of solids and ices in the disk. The key response of the disk to gap opening that will be investigated is its thermal structure and how perturbations to this will shift disk chemistry in the vicinity of the planet.

Project details:

1. The student will work with an existing 2D disk radiative transfer model, MCMax, to calculate the temperature structure of protoplanetary disks.

2. Physically motivated modulations to the surface density profile of the disk will be investigated in light of giant planet formation and the thermal structure recomputed. Gap depths and widths will be informed by parameterisations from dynamical simulations.

3. A model of water, carbon, and nitrogen chemistry in disks will be produced and used to post-process the thermal disk models for their effect on the composition of solids and ices in the vicinity of the gaps.

4. These predictions of how gaps affect dust composition in disks will be compared with observations from the solar system, exoplanets, and accreting stars.

5. There is scope to generalise these results, considering disks of different mass, stars of different spectral type, and planets of different sizes to provide an ensemble of predictions as a reference point for future exoplanet observations from missions such as JWST.

Example disk density structure from MCMax. In this case in the absence of a giant planet introducing a gap.
Skills required:

Experience of a programming language such as Python will be valuable for visualisation and analysis of model results. The underlying disk code is written in Fortran, whilst there is no need to modify this code to achieve the project’s core aims, there is the potential to modify it to achieve some of the later aims.

During the initial stage of the project, you will need to become familiar with the basic equations and processes governing the structure of protoplanetary disks, in particular in relation to how planets influence their surface density.

Useful references:

- A grand synthesis of solar system observations, utilising Jupiter’s opening of a gap as a key explanatory factor in producing the compositional characteristics of meteorites we see today.

- A recent parameterisation of how giant planets influence disk surface density structure.

Min et al., Radiative transfer in very optically thick circumstellar disks, Astronomy and Astrophysics, doi:10.1051/0004-6361/200811470 (2009)
- A description of the Monte Carlo radiative transfer code used to model disk structure.

Kruijer et al., (2017). Age of Jupiter inferred from the distinct genetics and formation times of meteorites, PNAS, doi:10.1073/pnas.1704461114
- A paper providing the observational basis for thinking that Jupiter opened a gap in the early solar system, thus chemically isolating the inner and outer regions of the disk.

- A classic paper providing a simple model of snowlines in disks and how they map into planetary composition.

- A first exploration of the thermal effect of gaps in disks.

General references:


Characterising the properties of protoplanetary discs with ALMA

Supervisor I: Marco Tazzari (H32, mtazzari@ast.cam.ac.uk)
Supervisor II: Richard Booth (H35, rab200@ast.cam.ac.uk)
UTO: Cathie Clarke (H10, cclarke@ast.cam.ac.uk)

Project summary:
Planets form in the dust-rich gaseous discs that orbit young stars at the end of the star formation process. In the last three years the ALMA telescope spatially resolved hundreds of protoplanetary discs for the first time at sub-mm/mm wavelengths, providing new insight into the spatial distribution of dust grains in discs. Understanding how dust grains evolve in discs is the next big step needed to further our understanding of planet formation.

However, inferring the radial profile of the dust continuum emission from ALMA observations is hindered by biases introduced by the observational setup and the analysis technique, both of which have been poorly characterised so far. In this project you will learn how to analyse ALMA observations of protoplanetary discs with state-of-the-art modelling techniques and characterize the biases that affect all measurements of disc properties.

Project description:

Background:
The Atacama large millimeter and sub-millimeter array (ALMA) has revolutionised our view of protoplanetary discs by delivering unprecedented resolution and sensitivity. The former led to the surprising discovery that discs are characterised by rich substructures such as rings, gaps, and spiral arms (Clarke et al. 2018; Andrews et al. 2018b). The latter enabled us to spatially resolve hundreds of protoplanetary discs in multiple star forming regions, bringing a new statistical perspective to protoplanetary disc studies (e.g., Ansdell et al. 2016; Tazzari et al. 2017).

Being sensitive to the emission of dust grains in protoplanetary discs, ALMA can uniquely probe the bulk of the rocky material available for the planet formation, providing constraints for theories of disc evolution and planet formation. The radial profile of a disc continuum emission at sub-mm/mm wavelengths informs us of the spatial distribution of dust. In particular, the spatial extent of the emitting region (namely, the size of a disc) and the shape of the brightness radial profile are crucial quantities that can be used to detect where dust is located and how much it has grown (grain growth from sub-micron sizes typical of interstellar medium to large rocky bodies is the first step in the planet formation process).

The resolution and sensitivity of the observations and the technique used to fit them are likely to introduce biases that need to be characterised in order to put firm constraints on the discs’ structure. Given the large samples of disc observations now available, controlling these biases is a crucial step toward a robust understanding of the growth and migration of solids in discs. This project is aimed at providing an empirical characterisation of these biases.
Project details:
ALMA is the most powerful sub-mm interferometer ever. Unlike single dishes that essentially take pictures of the sky, interferometers measure the Fourier Transform of the sky, sampling it at the discrete locations where the antennas are located. A direct fit of the interferometric measurements (so-called visibilities) is the most robust way to fit observations with a disc model, however the biases involved in the process have not been constrained so far.

The main goals of this project are:
1. to characterise how well we can measure the brightness radial profile of a protoplanetary disc for different ALMA observational setups;
2. to study how sensitive ALMA observations are to different disc morphologies;

You will build a suite of simulated ALMA observations of a toy-model protoplanetary disc and then to fit the simulated datasets as if they were real observations, using state-of-the-art code libraries (GALARIO, Tazzari et al. 2018) to test how well the structure of the underlying disc model is captured by the observations and recovered by the fits.

You will apply this approach to characterise the biases in two ways:
• (goal 1) keeping the disc model fixed, you will simulate observations with a range of resolutions and sensitivities, reproducing observations typical for both surveys, and dedicated single-source observing programmes.
• (goal 2) by varying the disc morphology (e.g., shallow or steep outer edge), you will test what is the best combination of resolution and sensitivity to be used when observing these discs, and what is the best functional form for the brightness radial profile for fitting the observations.

Possible further avenues of research depending on your interests and time available are:
• to investigate if the grain growth estimates in literature have been affected by the biases characterised in goals 1 and 2;
• to investigate how azimuthal asymmetries affect disc size measurements.

Figure: Disc structures recently unveiled by ALMA at extreme high-resolution (Andrews et al. 2018). Full gallery here: https://almascience.eso.org/almadata/lp/DSHARP/

Skills required:
Familiarity with the Python language; reading/writing datasets with numpy; making plots.

Useful references:
Tazzari, Beaujean, and Testi, 2018 MNRAS 476 4527

General references:
Andrews 2015, PASP 956 961
Testi et al. 2014, Protostars and Planets VI, pp. 339
Double Diffusive Mixing in Stars

Supervisor: Christopher Tout, H61, email: cat@ast.cam.ac.uk

Project Summary:
Convective processes remain one of the poorly understood aspects of stellar evolution. The mixing length theories used in stellar evolution models rely on a calibration to the Sun. In practice this calibration fixes the radius of the star by determining the adiabat on which most of the convective envelope lies. A similar approximation extrapolated to other stars very well explains the qualitative evolution of later stages. Nevertheless the quantitative behaviour of evolved stars depends on how convection is modelled. In this project you will systematically investigate, with the Cambridge STARS code, the effects of convection in the presence of composition gradients or semiconvection.

Project Details:
In a star of uniform composition convective boundaries are identified by the Schwarzschild criterion such that material is convective when 
\[ \nabla_a < \nabla_r, \]  
where
\[ \nabla_a = \left( \frac{\partial \log T}{\partial \log P} \right)_S, \]  
the adiabatic gradient of temperature \( T \) with pressure \( P \) which can be found from the equation of state of stellar material, and
\[ \nabla_r = \left( \frac{d \log T}{d \log P} \right)_r = \frac{3 \kappa}{16 \pi a c G T^4} \frac{P L_r}{m}, \]
depending also on opacity \( \kappa \) and local luminosity \( L_r \), which must be found from the structure of the stellar model. In the presence of a composition gradient characterized by the the change in molecular weight \( \mu \) the Ledoux criterion for convection when
\[ \nabla_a < \nabla_r + \frac{\varphi}{\delta} \nabla_\mu, \]
where
\[ \delta = \left( \frac{\partial \log \rho}{\partial \log T} \right)_{P,\mu} < 0, \]  
\[ \varphi = \left( \frac{\partial \log \rho}{\partial \log \mu} \right)_{P,T}, \]
and
\[ \nabla_\mu = \frac{d \log \mu}{d \log P}, \]  
is often used instead. In practice it is likely that the stabilising nature of the composition gradient can be overcome by double diffusive mixing similar to thermohaline mixing in the Earth’s oceans but the rate at which material is mixed in stars remains uncertain. In the STARS code mixing is carried out by diffusion so altering the diffusion coefficient in semiconvective regions can mimic its effect. At present the Ledoux criterion and reduced mixing is not included in the STARS code and a major part of this project will be to include it. This will require understanding and modifying the equation of state routines and the package to set up and solve the non-linear differential equations governing stellar evolution. STARS is written in FORTRAN 77, a straightforward language to understand and use.

Once this has been successfully achieved the code can be run on a variety of stellar models with differing treatments of semi-convection to understand and quantify the effect of different physical choices. In the first instance application will be made to the growing convective core during helium burning in intermediate mass stars. Effects on the size of the final helium exhausted core are critically important for the onset of thermal pulses on the asymptotic giant branch and the formation of carbon stars.
Related Courses:
Details of the physics of convection will be covered in the part III Structure and Evolution of Stars course.

Skills required:
Computational, both modelling and analysis of results.

* Understand convection, semiconvection and extra mixing in stars.
* Learn how to use and modify the Cambridge STARS stellar evolution code.

References:
Eldridge J. J., Tout, C. A., Structure and Evolution of Stars, 2019, World Scientific (Sections 4.4 and 7.1)

Figure 1: Semiconvection outside a convective hydrogen-burning core. The hydrogen abundance $X$ in the core has been depleted relative to the surface of the star. Material is hot and fully ionized with $\nabla_a = \text{const}$ and opacity dominated by electron scattering so that $\nabla_r \propto \kappa_{es} \propto 1 + X$. In the helium rich core $\nabla_r$ falls monotonically with radius until at mass $m_1$ the Schwarzschild criterion is satisfied at the edge of the convective core. The red solid lines show the state when the Schwarzschild criterion is strictly applied. No helium is mixed from the core to $m > m_1$. Just outside the core the opacity is higher, because $X$ is larger, and there is another convective region $m_1 < m < m_2$. However a small amount of mixing across the boundary at $m_1$ reduces $\nabla_r$ in this region and its outer boundary moves inwards. Small bursts of repeated mixing leave behind the equilibrium composition profile shown in blue that ensures $\nabla_r = \nabla_a$. 

$\Delta r \Delta a \Delta a \Delta r \Delta r \Delta a$
The Faint Young Sun Problem

Supervisor I: Christopher Tout (H61, cat@ast.cam.ac.uk)
Supervisor II: James Pringle (jep@ast.cam.ac.uk)
UTO: Christopher Tout

Project summary:
Models of the Sun generally show that it has been gradually increasing in luminosity since it began to fuse hydrogen to helium some 4.7Gyr ago when it's luminosity was only 0.7 what it is now. This makes the existence of liquid water and the origin of life only 400Myr after the Sun formed difficult. Feulner (2012) gives a comprehensive review of the problem. Feulner used a formula fitted by Gough (1981) to model the change in luminosity of the Sun over time. This formula remains a good fit to standard solar models but does not give us any idea of the uncertainty in its predictions. This project looks at the evolution of standard solar models using the Cambridge STARS stellar evolution code to investigate by how much the early luminosity of the Sun might be varied while remaining consistent with measurements of the present day Sun.

Project description:
You will use the Cambridge STARS code to make detailed evolutionary models of the Sun from formation up to its present day state and thence determine the history of the solar luminescence. You will vary the initial conditions and the physics included within the models within reasonable ranges and possibilities to place bounds on the possible luminosity of the Sun in past that can be used as input to models of the Earth.

Background:
The Sun is now 4.6 Gyr old and has been increasing in luminosity since it was born about 30% fainter than it now is. Much can be measured very precisely for the present day Sun but there remains uncertainty about its past. Standard solar models were successfully used to identify the solar neutrino problem that led to the discovery that neutrinos oscillate between types and so must have mass (Pallavicini 2015) but these models actually used a composition for the Sun that differs from what is apparently measured at its surface today (Asplund et al. 2009). So there remains room to vary our models.

Project details:
You will first learn to use and understand the Cambridge STARS code to evolve stars. With the code you will evolve models of the Sun from the pre-main sequence that have the correct characteristics, particularly luminosity and radius, but also other measurable quantities such as the depth of the convective envelope. This requires adjustment of the composition which mainly affects the luminosity and the mixing length parameter which, by changing the adiabat on which most of the convective envelope lies, changes the radius. You should devise empirical fitting formulae for the luminosity and temperature of the Sun that can be used to describe the radiation reaching the Earth over its lifetime. This will require setting up a method to evolve many models while varying conditions to converge on the correct luminosity and radius. Most importantly by varying the input parameters you should determine the variations in past luminescence that can be accommodated by present-day observations. The project can be extended by altering the less established physics, including the effects of rotation on structure and mixing. In some cases this will require modifying the code which is written in FORTRAN 77.
Skills required:
Computational. Understand and run the Cambridge STARS stellar evolution code. Write code to run models and converge on particular parameters. Write code to fit analytic formulae to output data. If time permits, modify the STARS code to include new physics. The Structure and Evolution of Stars Course has some relevance but is not required.

Useful references:

General references:
Pallavicini M., 2015, J. Phys.:Conf. Ser., 598, 012007
Project summary:

In the last few years, a new class of astrophysical object has been discovered: ultraluminous X-ray pulsars. This population is enigmatic, with only six identified to-date, and they are poorly understood. In particular, they appear to exceed the theoretical Eddington limit for the neutron stars that power them by factors of 100 or more. The main goal of this project is to compile a sample of ultraluminous X-ray sources (ULXs) from the recently released Chandra Source Catalogue (v2) to help grow this new and currently tiny sample of ULX pulsars.

Background:

Ultraluminous X-ray sources (ULXs) are an unusual population of astronomical objects seen in external galaxies that are extremely bright in the X-ray band (see Kaaret et al. 2017 for a recent review). These sources are so bright that they were widely expected to be powered by accretion onto a black hole of some kind. However, they have always been difficult to explain, as they comfortably exceed the Eddington limit (the point at which simple theory tells us outward radiation pressure should equal the gravitational attraction of the central object, and should therefore prevent the source from exceeding some luminosity, $L_E$) for the stellar-remnant black holes seen in our own Galaxy ($M \sim 10 M_{\odot}$), but they do not reside in the nuclear regions of these galaxies (Figure 1), so they cannot be powered by supermassive black holes ($M > 10^5 M_{\odot}$), for which the Eddington limit is much higher (as $L_E$ is proportional to $M$). Some authors therefore suggested that these ULXs might be powered by ‘intermediate mass’ black holes ($M \sim 1000 M_{\odot}$).

Recently, however, it has been discovered that a small number of these sources are powered by accreting neutron stars ($M \sim 1-2 M_{\odot}$), through the detection of coherent X-ray pulsations. Astonishingly, this means these sources appear to exceed their Eddington limits by factors of ~100 or more! It is not currently understood how these sources are able to radiate so brightly, given their relatively small masses. Only six such sources are currently known: M82 X-2 (Bachetti et al. 2014), NGC 7793 P13 (Fuerst et al. 2016, Israel et al. 2017a), NGC 5907 ULX1 (Israel et al. 2017b), NGC 300 ULX1 (Carpano et al. 2018), NGC 1313 X-2 (Sathyaprakash et al. 2019) and M51 ULX-7 (Rodríguez Castillo et al. 2019). However, the discovery of these sources leads to the natural conclusion that a much larger number of the ULX population are probably also powered by neutron stars.

Growing this sample will be a key step in understanding these remarkable sources further, and an important part of this process is to assemble the largest sample of ULXs possible. The most recent ULX catalogue available has been compiled from observations taken with ESA’s XMM-Newton X-ray observatory (Earnshaw et al. 2019). However, the superior imaging capabilities of NASA’s Chandra X-ray observatory mean it is more sensitive to faint point sources in crowded regions, and is therefore ideally suited to the search for ULXs. The primary goal of this project is to compile a sample of ULXs from the Chandra archive, utilizing in particular the recently released Chandra Source Catalogue (v2).
Project details:

The student will work on compiling a new sample of ultraluminous X-ray sources from the recently released *Chandra* Source Catalogue (v2, hereafter CSC2), a compilation of all the X-ray sources detected by *Chandra*. This will involve cross-matching CSC2 with catalogues of known local galaxies, in order to identify their X-ray source populations, and among them the ULXs. Simple analyses of the derived source population will then be performed, in order to compare with the existing ULX population. More detailed analyses (e.g. spectroscopy, variability studies) of interesting individual candidates identified during the project may follow, depending on progress.

![Optical image of the galaxy IC 342, with X-ray data from the NuSTAR satellite overlaid in magenta. Two very bright X-ray sources (ULXs) can be seen in the spiral arms of the galaxy.](image)

**Figure 1:** Optical image of the galaxy IC 342, with X-ray data from the *NuSTAR* satellite overlaid in magenta. Two very bright X-ray sources (ULXs) can be seen in the spiral arms of the galaxy.

Skills required:

The project involves utilizing catalogued data from a variety of sources; experience with Unix-based computing and basic programming (e.g. Python) is desirable, but not a strict/formal requirement as this can be developed.

Useful references:

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 include comparing the set of PN with improved direct distances and using these to recalibrate a range of secondary distance methods.

Project description:
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 second major Gaia Data Release (Gaia DR2) was released April 2018, providing parallax information for \( \sim 1.3 \) 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 \( \geq 0.5 \) 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.

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**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: N Chornay
This project will investigate the sample of Milky Way PN central stars that we (Chornay & Walton, 2019) have matched to Gaia sources. The sample includes several hundred PN with confident matches and several hundred with probable matches. Figure 1 shows the location of these PN. For the PN matched to Gaia sources, improved distances will result. This will allow an analysis of how this sample of PN with Gaia parallaxes will improve the PN Luminosity Function (PNLF) of Galactic PN (Ciardullo, 2012). This impacts on the use of PN as standard candles, and their use in providing a standard distance technique applicable to both young (population 1) and old (population 2) galaxies.

In addition the project will investigate the sample of PN with Gaia parallaxes to update the physical parameters of these nebulae, based on the improved distances. In particular the properties of the Type I PN will be updated, these likely result from the evolution of more massive stars.

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.

Project details:

1. From the catalogue of PN with central stars observed by Gaia in Gaia DR2, 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 measurement. 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. For the catalogue sample of PN with only a probable match to a Gaia source, investigate the properties of the PN.
5. Compare distances from Gaia parallaxes to distances for these PN obtained from a range of indirect measures, e.g. reddening and/or Ha surface brightness techniques to determine distance to the PN. This will lead to a recalibration of these indirect techniques for determining PN distances.

The project will involve extensive use of ESA Gaia data (http://gea.esac.esa.int/archive/). Gaia DR2 will be available during the project.

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 courses in “Astro Statistics” and “The Structure and Evolution of Stars” are relevant to this project.

Useful references:

- 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](http://www.cosmos.esa.int/web/gaia/iow_20141205)
### Project summary: Tidal disruption events

Tidal disruption events occur when a star passes so close to a supermassive black hole that the tidal forces overcome its self-binding energy. As a result, the star is destroyed and part of the material is accreted, leading to transient multi-wavelength emission. However, so far the mechanism responsible for the luminous UV/optical emission is not known and its properties are poorly understood. Recent advances in both detection rate and multi-wavelength follow-up have resulted in a significant number of tidal disruption events having well-sampled Swift UV/optical light curves. Swift is a space-based (low Earth orbit) optical, UV and X-ray observatory, dedicated to the follow-up of transient events such as TDEs. The aim of this project is to build a pipeline that analyses these light curves in a systematic way, in terms of de-reddening, host galaxy subtraction, blackbody fitting etc. Once this is done, we can investigate correlations between observable properties, such as the peak luminosity, temperature, decline rate, emission radius etc with fundamental properties such as the black hole and disrupted stellar mass. These correlations can help inform us on the physical processes driving the radiation.

### Background: Tidal disruption events

When a star passes too close to the supermassive black hole (SMBH) lurking in the centre of a dormant galaxy, it gets shredded by the SMBH tidal forces in what is called a tidal disruption event (TDE). In the ensuing evolution, about half of the debris is gravitationally bound to the black hole and therefore falls back and is ultimately accreted, while the other half is unbound (Rees, 1988). Observationally this is witnessed as a luminous flare of emission ranging from radio through mm, IR, UV/optical and X-ray wavelengths from an otherwise quiescent galaxy. This sudden supply of material implies that the accretion rate goes from negligible (before the flare) to (sometimes highly) super-Eddington and back on a timescale of months/years. This allows us to study extreme accretion processes around SMBHs on human (even grad student) timescales, in contrast to the typical evolution timescales of active galactic nuclei (order ~10^7 years).

However, the field of TDEs is young and there are a number of gaps in our understanding, even regarding the most basic of properties. For example, it is unclear what produces the copious amounts of UV/optical radiation observed, as are what (external and/or internal) factors determine their observational appearance. One group of models invoke the reprocessing of accretion power by a dense medium at larger distances (either static or outflowing), but this is at odds with the observed correlations (specifically, time lags) between different wavelengths in at least 1 source. In these models the X-ray brightness depends sensitively on the viewing angle of the observer with respect to the plane of the accretion flow.

A different group of models argue instead that stream-stream collisions, which are bound to occur when the material wraps around the SMBH multiple times, are the source of the UV/optical emission (due to strong shocks).
On a more fundamental level, powering the UV/optical emission as reprocessed accretion power predicts certain correlations between SMBH properties and TDE properties, for example the fall-back rate (and hence lightcurve decay rate) should scale inversely proportional to the SMBH mass; another example is an expected correlation between SMBH mass and temperature.

Project details:
This project is entirely data-driven and will involve reducing Swift satellite data from scratch, performing galaxy template fitting to host galaxy photometry to synthesise the galaxy brightness in bands that were not explicitly observed. Then we will fit blackbody models to the light curve at each epoch, extracting physical parameters such as the emission temperature, luminosity and radius (For an example of a light curve, see the figure above).

A general step by step outline could look as follows:
- Perform aperture photometry (using existing pipeline) for all the available swift data for TDEs (sample of ~15), correct for reddening and other potential systematics.
- Collate host galaxy photometry from the literature, and do broad-band stellar population modelling [code needs to be written].
- Synthesise photometry and subtract host galaxy contribution from lightcurves.
- Blackbody fitting to light curves, extracting physical parameters
- Investigate correlations between observables, such as SMBH mass, T, L, Eddington fraction, lightcurve decay rate, etc.

- if there is time there is also scope for detailed lightcurve modelling to extract physical parameters using existing TDE lightcurve models.
Skills required:

Some code needs to be written, so familiarity with Python (or similar) is preferred. Knowledge of aperture photometry and synthetic photometry would be useful, but not required.

Useful references:
Rees, 1988, Nature, 333, 523
Holoien et al., 2016a, MNRAS, 455, 2918

General references:
Project timetable format and Content

A compulsory element of the course is a substantial research project, extending over two terms. This is undertaken with the guidance of a supervisor from the Institute of Astronomy. The research project accounts for a third of the total marks available for the course. Each year the Institute produces a booklet containing descriptions of the individual projects available. Each entry contains a brief description of the background to the project along with a summary of the type of work involved and several references to where more information can be obtained. Following the project descriptions, details of the timetable, format of the project write-ups and the criteria to be used in the assessment of the projects are included.

Please read the University's guidelines on plagiarism.

Project Timetable

Michaelsmas Term

An orientation course (5 lectures) covering unix, the Institute of Astronomy Science Cluster, LaTeX (text-processing facility) and information resources available on-line commences on the first Tuesday of Michaelmas Full Term (see online timetable and calendar).

Choice of up to ten projects, in rank order, should be handed to the Course Secretary by 12pm on the second Friday of Michaelmas Full Term (18 October 2019). Students who do not supply rank-ordered choices by the deadline will be allocated a project by the Project Coordinator.

Notification of approval of project choice will be made by e-mail no later than the third Tuesday of Michaelmas Full Term (22 October 2019). The equivalent of 3 formal Supervisions will be offered by the Project Supervisor in the Michaelmas Term.

An interim progress report, length no more than 1,000 words, bearing the signature(s) of the main supervisor(s) and second supervisor, must be handed to Fatima Rasool no later than the last day of Michaelmas Full Term (6 December 2019). The report should be produced with LaTeX, or an equivalent text-processing package and may contain material that can be incorporated in the final project report. The interim 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 report to reiterate the material given in the Project Handbook. The interim reports do not constitute part of the formal assessment but are regarded as an essential part of the monitoring procedure.

Lent Term

The equivalent of 3 formal Supervisions will be offered by the Project Supervisor.

Practice oral presentations, consisting of a 20 minute talk followed by up to 10 minutes of questions, to an audience of Part III Astrophysics students, Project Supervisors and the Project Coordinator will be given on the last Tuesday, Wednesday, Thursday and Friday of Lent Term (10, 11, 12, 13 March 2020). A final timetable for the presentations will be provided by e-mail during the previous week. The presentation is not formally assessed but offers the opportunity to become familiar with the format of the presentation, to be assessed by the Part III Examiners in the Easter Term. The Project Supervisor’s attendance at the informal presentation and subsequent feedback constitutes the fourth and final, Supervision of the Lent Term.
A draft of the final project report, generated with LaTeX or an equivalent text-processing package, should be handed to the Project Supervisor no later than 15 April 2020. This last Supervision, to discuss the draft report, should take place no later than the first Tuesday of Easter Full Term (21 April 2018). Two copies of the final project report must be handed, in person to the Course Secretary no later than 12 pm on the second Tuesday of Easter Full Term (28 April 2020). Late submissions must be submitted via your College Tutor with an accompanying letter of explanation from the Tutor. Your University Examination Number must NOT appear anywhere in the report or on the cover sheet.

A formal, assessed, oral presentation to Part III Astrophysics Examiners will take place on the second Thursday or Friday of Easter Full Term (note if required orals may also take place on the preceding Wednesday). A final timetable for the presentations will be provided via e-mail during the previous week. The presentation should consist of a 20 minute description of the project with PowerPoint or equivalent on a laptop computer. The presentation will be followed by up to 10 minutes of questions. The Examiners will allocate approximately 15% of the total marks for the project on the basis of the presentation. The NST Part III Astrophysics Examiners meeting takes place on Tuesday 16 June 2020 TBC.

Project reports may be collected from the Course Secretary after 9.30 am on Wednesday 17 June 2020.

Project Report Format and Content

The 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 report must be produced with LaTeX, or another text processing package, and must not exceed 30 pages in length, including Figures, Tables, References and any Appendices. The minimum acceptable font size is 11pt with at least single line spacing. 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.

The submission should be logically structured, clear and complete, while remaining concise. 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.

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 guidance on what constitutes plagiarism, see http://www.admin.cam.ac.uk/univ/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.

Each report (two copies) must be accompanied by a cover sheet that should bear (1) the title of the
project, (2) your name, (3) your college, (4) your home address and (5) a signed declaration that reads:
I declare that this project report represents work undertaken as part of the NST Part III Astrophysics
Examination. It is the result of my own work and, includes nothing which was performed in
collaboration. No part of the report has been submitted for any degree, diploma or any other
qualification at any other university. I also declare that an electronic file containing this work has been
sent by email (ugadmin@ast.cam.ac.uk) on this date.
Signed................
Date ..................

If you are in any doubt as to whether you can sign such a declaration you should consult the Part III
Coordinator before submitting your report. In the event that your project report is not collected after
examinations the report will be sent to the address provided on the cover sheet.
Examiners’ Criteria for Marking the Project Report and Oral Presentation

The project element of the NST Part III Astrophysics course constitutes one third of the course (equivalent to the marks assigned to two 24-lecture Mathematics Part III lecture courses). Approximately 15% of the marks for the project will be assigned on the basis of the assessed oral presentation that takes place in the Easter Term. The balance of the marks will be assigned on the basis of the written project report. 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

Students should be aware that the set examination timetable will be adhered to. In the case of genuine illness college tutors should make a proper representation to the Senior Examiner, which would be taken into account, otherwise no marks will be allowed for students who fail to attend the oral presentation examination.

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
## Supervisor Contact List

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