Institute of Astronomy
University of Cambridge

Natural Sciences Tripos Part
III/MASt Astrophysics Project
Booklet

Version date: 27th September 2018

2018-2019

Editors: George Efstathiou and Fatima Rasool
<table>
<thead>
<tr>
<th>#</th>
<th>Primary Supervisor</th>
<th>Secondary Supervisor</th>
<th>Assoc.UTO/Su prvisor</th>
<th>Project Title</th>
<th>Page No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Banerji, Manda</td>
<td>Hewett, Paul</td>
<td>Hewett, Paul</td>
<td>Dust Obstruction &amp; Host Galaxy Properties of Luminous, High Redshift Quasers</td>
<td>5-6</td>
</tr>
<tr>
<td>2</td>
<td>Belokurov, Vasily</td>
<td>Koposov, Sergey</td>
<td>Belokurov, Vasily</td>
<td>“Chemistry From Colour” – precise metallicities for halo stars from photometry only with Machine Learning</td>
<td>7-9</td>
</tr>
<tr>
<td>3</td>
<td>Booth, Richard</td>
<td>Clarke, Cathie</td>
<td>Clarke, Cathie</td>
<td>Planet formation under the influence of external photo-evaporation</td>
<td>10-11</td>
</tr>
<tr>
<td>4</td>
<td>Breedt, Elme</td>
<td>Hodgkin, Simon</td>
<td>Gilmore, Gerry</td>
<td>Cataclysmic Variables in Gaia DR2</td>
<td>12-13</td>
</tr>
<tr>
<td>5</td>
<td>Busso, Giorgia</td>
<td>De Angeli, Francesca</td>
<td>Irwin, Mike</td>
<td>Searching for Extremely Metal-Poor stars in the Galactic halo with Gaia</td>
<td>14-16</td>
</tr>
<tr>
<td>6</td>
<td>Challinor, Anthony</td>
<td>Sherwin, Blake</td>
<td>Challinor, Anthony</td>
<td>Constraining primordial non-Gaussianity with CMB lensing and large-scale structure</td>
<td>17-19</td>
</tr>
<tr>
<td>7</td>
<td>Clarke, Cathie</td>
<td>Booth, Richard</td>
<td>Clarke, Cathie</td>
<td>Assessing the mobility of dust and gas in protoplanetary discs</td>
<td>20-21</td>
</tr>
<tr>
<td>8</td>
<td>Clarke, Cathie</td>
<td>Tout, Chris</td>
<td>Clarke, Cathie</td>
<td>Understanding the accretion of gas on to young stars</td>
<td>22-24</td>
</tr>
<tr>
<td>9</td>
<td>DeGraf, Colin</td>
<td>Sijacki, Debora</td>
<td>Sijacki, Debora</td>
<td>Seed formation of supermassive black holes</td>
<td>25-27</td>
</tr>
<tr>
<td>10</td>
<td>Del Zanna, Giulio</td>
<td>Efstathiou, George</td>
<td></td>
<td>The heating and cooling cycles in solar active region plasma</td>
<td>28-30</td>
</tr>
<tr>
<td>11</td>
<td>Diener, Catrina</td>
<td>Murphy, David</td>
<td>Irwin, Mike</td>
<td>Moths to a flame Clustering of z~2 galaxies around luminous QSOs</td>
<td>31-33</td>
</tr>
<tr>
<td>12</td>
<td>Efstathiou, George</td>
<td>Gratton, Steven</td>
<td>Efstathiou, George</td>
<td>Redshift Space Distortions: Constraints on (\sigma_8)</td>
<td>34-35</td>
</tr>
<tr>
<td>13</td>
<td>Evans, Wyn</td>
<td>Sanders, Jason</td>
<td>Evans, Wyn</td>
<td>Dynamical Models of Galactic Bars</td>
<td>36-37</td>
</tr>
<tr>
<td>14</td>
<td>Gilkis, Avishai</td>
<td>Tout, Chris</td>
<td>Tout, Chris</td>
<td>The structure and properties of massive stellar envelopes: convection, radiative transport, and the roles of opacity and ionization</td>
<td>38-39</td>
</tr>
<tr>
<td>No.</td>
<td>Authors</td>
<td>Title</td>
<td>Reference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Gilks, Avishai Tout, Chris Tout, Chris</td>
<td>Collisions of neutron stars and red giants: stellar properties at collision, occurrence rates, and sensitivity to supernova dynamics</td>
<td>40-41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Gilmore, Gerry Worley, Clare Gilmore, Gerry</td>
<td>Are the first stars hiding behind later pollution?</td>
<td>42-43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Gilmore, Gerry Pebody, Gudrun; Gonneau Anais; Worley, Clare; Hourihane, Anna Gilmore, Gerry</td>
<td>Were Eddington and Dyson correct in 1919?</td>
<td>44-45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Gonzalez-Fernandez, Carlos Hodgkin, Simon Irwin, Mike</td>
<td>Variability in Star Formation Sites: A Search for FU Orionis stars</td>
<td>46-48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Gratton, Steven Efstathiou, George Efstathiou, George</td>
<td>Point Source Masking in Planck</td>
<td>49-51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Haehnelt, Martin Gaikwad, Prakash Haehnelt, Martin</td>
<td>Probing QSOs with opacity fluctuations in the helium Lyman-alpha forest</td>
<td>52-54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Halabi, Ghina Gonzalez-Fernandez, Carlos Tout, Chris</td>
<td>Can Gaia data solve the mystery of the stellar breathing pulses?</td>
<td>55-56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Hewett, Paul Banerji, Manda Hewett, Paul</td>
<td>Host galaxy properties derived from a statistical analysis of quasar spectra and photometry</td>
<td>57-58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Hodgkin, Simon Koposov, Sergey Belokurov, Vasily</td>
<td>Unlocking the Transient Sky</td>
<td>59-61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Kama, Mihkel Folsom, Colin Clarke, Cathie</td>
<td>A new window on the composition of planets and disks</td>
<td>62-63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Kama, Mihkel Shorttle, Oliver Clarke, Cathie</td>
<td>A Song of Ice and Fire: Sulphur in protoplanetary disks</td>
<td>64-65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Kama, Mihkel Shorttle, Oliver</td>
<td>Giant planets and the composition of planet-forming disks</td>
<td>66-67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Lansbury, George Walton, Dominic Fabian, Andy</td>
<td>The search for hidden supermassive black hole growth in quasars</td>
<td>68-69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Madhusudhan Nikku Madhusudhan Nikku</td>
<td>High-temperature Chemistry in Exoplanetary Atmospheres</td>
<td>70-71</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>McMahon, Richard</td>
<td>Pons, Estelle</td>
<td>McMahon, Richard</td>
<td>Measuring the sizes of ionized hydrogen near zones in high redshift quasars in the epoch of reionisation</td>
<td>72-73</td>
</tr>
<tr>
<td>---</td>
<td>------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>30</td>
<td>Meerburg, Daan</td>
<td>Coulton, Will</td>
<td>Efstathiou, George</td>
<td>Calibrating the cosmological collider experiment</td>
<td>74-76</td>
</tr>
<tr>
<td>31</td>
<td>Parry, Ian</td>
<td>Parry, Ian</td>
<td></td>
<td>A lab prototype of a self-aligning space telescope (SUPERSHARP)</td>
<td>77-79</td>
</tr>
<tr>
<td>32</td>
<td>Reynolds, Chris</td>
<td>Alston, William</td>
<td>Reynolds, Chris</td>
<td>Unlocking the mysteries of optical/UV variability in quasars</td>
<td>80-81</td>
</tr>
<tr>
<td>33</td>
<td>Sanders, Jason</td>
<td>Evans, Wyn</td>
<td>Belokurov, Vasily</td>
<td>Chemical signature of a dwarf galaxy merger onto the Milky Way</td>
<td>82-83</td>
</tr>
<tr>
<td>34</td>
<td>Sijacki, Debora</td>
<td>Bourne, Martin</td>
<td>Sijacki, Debora</td>
<td>Dynamical friction on supermassive black holes in galaxy formation simulations</td>
<td>84-85</td>
</tr>
<tr>
<td>35</td>
<td>Tout, Chris</td>
<td>Tout, Chris</td>
<td></td>
<td>Eccentricity Evolution during Wind Mass Transfer</td>
<td>86-87</td>
</tr>
<tr>
<td>36</td>
<td>Vasiliev, Eugene</td>
<td>Evans, Wyn</td>
<td>Evans, Wyn</td>
<td>Dynamical modelling of dwarf spheroidal galaxies</td>
<td>88-89</td>
</tr>
<tr>
<td>37</td>
<td>Walton, Dominic</td>
<td>Fabian, Andy</td>
<td>Fabian, Andy</td>
<td>Ultraluminous X-ray Pulsars and Super-Eddington Accretion</td>
<td>90-91</td>
</tr>
<tr>
<td>38</td>
<td>Worley, Clare</td>
<td>Hourihane, Anna; Van Leeuwen, Floor</td>
<td>Gilmore, Gerry</td>
<td>Gaia &amp; Gaia-ESO: Defining the members of Open and Globular Clusters</td>
<td>92-95</td>
</tr>
<tr>
<td>39</td>
<td>Worley, Clare</td>
<td>Sanders, Jason</td>
<td>Gilmore, Gerry</td>
<td>Gaia &amp; Gaia-ESO: Characterising the Milky Way Field</td>
<td>96-99</td>
</tr>
<tr>
<td>40</td>
<td>Wyatt, Mark</td>
<td>Vasiliev, Eugene</td>
<td>Wyatt, Mark</td>
<td>Reassessing the dust-free class III stars in young star forming regions</td>
<td>100-101</td>
</tr>
<tr>
<td>41</td>
<td>Wyatt, Mark</td>
<td>Marino, Sebastian</td>
<td>Wyatt, Mark</td>
<td>Bombardment of close-in super-Earths by comets scattered in by eccentric giant planets</td>
<td>102-103</td>
</tr>
</tbody>
</table>

**APPENDIX**

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

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>107</td>
<td>108</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Introduction

This booklet contains descriptions of the individual projects available in the academic year 2018/2019. 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.

George Efstathiou Part III/MASt Astrophysics Course Coordinator, Michaelmas term 2018
1. Dust Obscuration & Host Galaxy Properties of Luminous, High Redshift Quasars

Project summary: Luminous, dust-obscured quasars are a population of quasars that have been hypothesised to connect the highly star-forming dusty galaxy and unobscured, ultraviolet luminous quasar populations (e.g. Sanders et al. 1988). In this project we will use spectral energy distribution (SED) fitting in order to better understand the obscuration levels and host galaxy properties of high-redshift quasars. The project involves analysis of a statistical sample of hundreds of thousands of quasars with optical and infrared photometry in order to quantify the typical levels of dust obscuration in a large sample.

Project description: The project is observational in nature utilising large multi-wavelength, multi-variate datasets from a wide variety of ground and space-based telescopes. It is ideally suited to a student looking to gain experience in observational, extragalactic astronomy.

Background: Quasars signpost accretion onto the most massive supermassive black-holes in the Universe and the bolometric output from a quasar during these accretion phases can outshine the host galaxy of the quasar by several orders of magnitude. Understanding the host galaxies of the most luminous quasars therefore remains challenging. In the case of obscured quasars however, host galaxy signatures may be more readily visible (e.g. Wethers et al. 2018). With large statistical quasar samples now in place (e.g. Paris et al. 2018) as well as populations of obscured quasars with extensive multi-wavelength data (e.g. Banerji et al. 2014) it is timely to begin investigating the interplay between quasar obscuration and host galaxy emission in the high-redshift Universe.

Project details: A very large spectroscopically confirmed sample of half a million quasars is now in place from the Sloan Digital Sky Survey (SDSS) Data Release 14. Photometric data at optical and infra-red wavelengths exists for a significant fraction of the quasars and the student will fit models of quasar + host galaxy emission to these data to quantify the level of obscuration and host galaxy contribution in this large, statistically significant dataset. Once the fitting has been conducted we will want to explore degeneracies in fitting parameters as well as trends with quasar luminosity and redshift.

For a subset of these quasars photometric data is now becoming available over a much larger wavelength range going all the way from the X-ray to the radio. We will use the publicly available fitting code AGNFitter (Calistro Riveira et al. 2016) to model the emission from these quasars over a very large dynamic range in wavelength. The amount of data available for each quasar will vary significantly, with only non-detections (upper limits) available at certain wavelengths. An important goal of the project will be to understand what properties of the quasar host galaxies can reasonably be constrained with the available data and to quantify how much the conclusions depend on the number of photometric datapoints that are being used in the fit.

An additional complication that potentially affects the analysis is that data taken with different telescopes and facilities have very different spatial resolution and are therefore potentially tracing emission on very different spatial scales. We will test how different assumptions regarding the blending of sources in multi-wavelength data potentially affect the SED decomposition. If time permits, we will investigate more sophisticated fitting algorithms that explicitly allow us to model blended, multi-component sources in heterogeneous datasets (e.g. Drouart et al. 2018).
**Skills required:** No lecture courses are strictly mandatory for the project although it will be useful for the student to have some background in extragalactic astronomy (e.g. by attending a Galaxies or Cosmology lecture course). The student should be comfortable working with and manipulating large observational datasets and dealing with selection effects that are invariably present in these data. The project will involve writing scripts in e.g. Python, IDL or Matlab. The project is exploratory in nature and can take a number of different directions depending on what we find via initial investigations. The student should therefore be comfortable with such an open-ended, data-driven approach to research.

**References:**

---

**Figure 1:** Schematic representation of a quasar spectral energy distribution showing some of the different components that are often employed when fitting to photometric data.
2. “Chemistry From Colour” – precise metallicities for halo stars from photometry only with Machine Learning

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

Project summary:
Chemical abundances are too costly to collect for large numbers of stars over a large area of the sky. This precludes detailed studies of the stellar halo, a component of the Galaxy, which harbours precious information on the assembly history of the Milky Way from high redshift up to the present day. In this Project, the student will build a Machine Learning tool, which will allow stellar metallicity to be inferred, based on accurate broad-band photometry instead. The colours are now measured routinely for hundreds of millions of stars across tens of thousands of degrees on the sky. More specifically, the Project will take advantage of the recently released photometric data from the ambitious Dark Energy Survey and the spectroscopy from the Sloan Digital Sky Survey. The Project combines aspects of Stellar Astrophysics, Galactic Archaeology, Data Mining and Machine Learning.

Project description:
This Project would involve designing numerical/statistical tools (using Machine Learning techniques such as neural networks) to infer stellar metallicities based solely on the photometric measurements of stars. The metallicity information will be used to assign distances to halo stars and constrain their orbital properties. This in turn would allow us to understand how the Milky Way halo was assembled and how the orbitals of stars depend on their chemical composition.

Background:
The Milky Way is usually separated into three distinct components: the disk, the bulge and the halo. The Galactic halo contains Dark Matter, some gas and a handful of stars. While the Dark Matter in the halo dominates the Galactic mass budget, the stellar halo only contains 1% of the total stellar mass. Most of the stars in the halo are believed to have come from small satellites that were disrupted by the Milky Way’s tidal forces. Studying the properties of the stars in the MW halo allows us to decipher the history of accretion and learn about the properties of the smaller objects that donated their stars. However, measuring the properties of the stellar halo is tricky given that it contains very few stars most of which are at large distances from the Sun. Usually we dissect the halo using purely photometric datasets such as catalogues of stars with positions (RA, Dec) and magnitudes (logarithm of flux) in different broad-bands. Selecting the likely halo tracers allows us to broadly map the density of this stellar halo as well as identify some sub-structures (such as the tidal streams visible in Figure 1). A lot more information about the halo can be gleaned from the stellar spectroscopy. Using spectra, we can measure the chemical abundances of stars, as well as their stellar velocities. But collecting spectroscopy of large numbers of stars in the halo is prohibitively expensive and the current samples of halo stars are extremely small.

It turns out however that there is a shortcut, which allows us to determine stellar metallicities without obtaining stellar spectra. That requires using the high precision broad-band measurement of stellar flux. By fitting models to multi-dimensional flux data provided by imaging surveys we can recover metallicities of millions of stars in the MW halo. See Figure 2 illustrating how the stars of different chemical abundances occupy different parts of colour-colour diagram.
Figure 1. Density of stars in the MW halo. Colour represents approximate heliocentric distance. This map reveals remnants of many accretion events, in the form of stellar streams of different widths. It is conjectured that the streams’ progenitors fell into the Milky Way many billions of years ago. Using chemical abundances, it will be possible to determine i) what sort of objects the progenitors of the streams were, ii) when they were accreted onto the Galaxy and iii) how the star-formation proceeded at very high redshifts.

Figure 2. Distribution of stars in g-r vs r-z (stellar colour-colour) space. Each point in the diagram represents a single star and the point’s colour reflects the metallicity of the star (red = metal-rich, blue = metal-poor). Note that metal-poor and metal-rich stars occupy different parts of the diagram. This can be used to determine the metallicities for all stars with accurate measurements of griz magnitudes.

Project details:

Step-by-step, the project will involve the following.

1) Cross-match the Dark Energy Survey and DECam Legacy Survey catalogs with the SDSS spectroscopic survey.
2) Fit the relation between chemical abundances of stars and stellar photometry using various methods, such as random forest regression, polynomial regression and neural networks.
3) Assess the performance of various methods.
4) Compare the results with the theoretical expectations from stellar evolution models.
5) Characterize the uncertainties of the method and check whether the method can be used to infer a probability distribution of chemical abundances in the halo.
6) Define and characterize the purity and completeness of samples of low/high metallicity stars selected using photometry only.
7) Build the model to recover distances of stars from apparent magnitudes and chemical abundances.
8) Analyze the Gaia kinematics of the stars as a function of stellar metallicity using distances and abundances recovered from photometry.
9) (Optional) Build a probabilistic model of stellar photometry conditional on chemical abundances, using either neural network as a base, or Gaussian mixture model.

Skills required:
Programming in Python is desirable. Interest/skills in ML, Bayesian Inference and data-mining are also welcome.

Useful references:

General references:
Helmi 2008 [http://adsabs.harvard.edu/abs/2008A%26ARv..15..145H](http://adsabs.harvard.edu/abs/2008A%26ARv..15..145H) for Stellar Halo review
Belokurov 2013 [http://adsabs.harvard.edu/abs/2013NewAR..57..100B](http://adsabs.harvard.edu/abs/2013NewAR..57..100B) for Galactic Archaeology
### 3. Planet formation under the influence of external photo-evaporation

<table>
<thead>
<tr>
<th>Supervisor I: Richard Booth (H35, <a href="mailto:rab200@ast.cam.ac.uk">rab200@ast.cam.ac.uk</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervisor II: Cathie Clarke</td>
</tr>
<tr>
<td>UTO: Cathie Clarke (H10, <a href="mailto:cclarke@ast.cam.ac.uk">cclarke@ast.cam.ac.uk</a>)</td>
</tr>
</tbody>
</table>

**Project summary:**
The detection of systems of super-earths planets, including the remarkable TRAPPIST-1 system, favour new models of planet formation based on the accretion onto planets of millimetre to centimetre sized pebbles in protoplanetary discs. Although such models typically consider the formation of planetary systems in isolation, we know that stars are born in clusters, where the ultraviolet (UV) radiation from nearby massive stars can drive mass loss from protoplanetary discs.

In this project, we will investigate the influence of evaporation by external UV radiation on the evolution of pebbles in protoplanetary discs. We will use disc evolution models to study planet formation by pebble accretion around a range of stellar types and different environments, making connections between planet formation by pebble accretion and the observable properties of the discs in which they form.

**Project description:**

**Background:**
The recent detection of the remarkable TRAPPIST-1 system presents challenges for theories of planet formation, requiring the dust in protoplanetary discs to be converted into planets extremely efficiently. This is most easily achieved by pebble accretion (Ormel et al. 2017), requiring the efficient growth and transport of large pebbles to inner regions of the disc, where the planets can form.

While the growth of dust grains from micron sizes to pebbles in isolated discs is relatively well understood, the influence of environment on this process has been largely ignored. However, photoevaporation is expected to drive diversity in the disc evolution, and possibly planet formation, as different stars encounter different UV fields. In some cases, this can dramatically deplete the dust from the disc, reducing the mass budget available for the formation of systems like TRAPPIST-1 (Haworth et al. 2018). However, it is also possible that evaporation might promote planet formation at large distances by removing gas from the protoplanetary disc, but leaving behind pebbles (Carrera et al. 2017).

**Project details:**
We will use a model for the evolution of dust and gas in protoplanetary discs developed in Booth et al. (2017) to study the evolution of the mass budget available for planet formation under a variety of conditions. This will involve considering different properties such as disc size and mass, stellar mass, and considering different UV fields.

This will involve adding prescriptions for the evaporation by external UV radiation into the code. The code will be tested against previous results for the evolution of the gas (Clarke 2007) and dust in the absence of radial drift (Haworth et al. 2018). We will then investigate differences in the evolution of pebbles between models with and without external photoevaporation for a range of different conditions.

The results of the disc evolution models will be used to investigate the influence of photoevaporation on the growth of planets by pebble accretion. Some example systems that could be studied are super-earths and giant planets around both stars like the sun, or low mass stars like...
TRAPPIST-1. In particular, trends such as the masses of planetary systems or the occurrence of giant planets with stellar mass could be investigated.

Other aspects of the problem that could be explored depending on your interests include:

- Whether photoevaporation can help explain the origin of comets at wide orbits, such as those in the Kuiper Belt.
- How early the seeds of planet formation must be formed, and whether we expect that they should be observed in protoplanetary discs by ALMA
- How photoevaporation affects the evolution of protoplanetary disc masses in clusters.

Skills required:

The project will require running a suite of simple simulations using an existing code that is written in Python. Small amounts of code development will be required, and thus the student will need to have, or acquire familiarity with the Python programming language.

Useful references:

Booth et al. 2017 (MNRAS, 469, 3994)
Clarke 2007 (MNRAS, 376, 1350)
Facchini et al. 2016 (MNRAS, 457, 3593)
Haworth et al. 2018 (MNRAS, 475, 5460)

General references:

4. Cataclysmic Variables in Gaia DR2

| Supervisor I: Elmé Breedt (H34, ebreedt@ast.cam.ac.uk) |
| Supervisor II: Simon Hodgkin (H39, sth@ast.cam.ac.uk) |
| UTO: Gerry Gilmore (H47, gil@ast.cam.ac.uk) |

Background:
A Cataclysmic Variable (CV) star consists of a white dwarf accreting from a late type main sequence star, usually via an accretion disc. The accretion produces photometric variability on a wide range of timescales, from seconds (accretion flickering) to hours (the orbital period) and months to decades (disc outbursts). These outbursts are the result of a thermal instability which operates in the accretion disc, causing a brightening of several magnitudes in less than a day. How frequently these outbursts occur is characteristic of each system, and it is closely related to the mass transfer rate from the companion star to accretion disc. The outburst recurrence time therefore serves as a proxy for the mass transfer rate of the binary, which, in turn, can be used to infer the evolutionary state of the system. These large amplitude outbursts also offer an efficient way of detecting and characterising the faintest members of the CV population which is difficult to reach with spectroscopic surveys. The majority of these outbursting systems will be hydrogen-rich cataclysmic variables, but we also expect to find the much rarer ultra-compact helium CVs (also known as AMCVn stars) among them.

Project details:
Gaia’s second data release (April 2018) included brightness, colour and parallax (distance) information for more than 1.3 billion stars. Spectroscopy and light curves will be added in future data releases as well, but at the moment variability information is only available for a selected sample of about half a million stars. In order to explore the time domain more widely, the student will use public data from large area photometric surveys to search for variable objects in the Gaia data.

The starting point will be a colour-selected subset of the GDR2 data. Some variability indicators can be derived from the Gaia data itself, and for a fraction of the sample it will be possible to retrieve ~10yr long light curves from the Catalina Real Time Transient Survey as well. The student will use these light curves to construct a catalogue of accreting white dwarf binaries from their photometric variability, e.g. outbursts, eclipses, or ellipsoidal modulation. They may wish to explore this data even further if time allows, e.g. by searching for periodic signals in the light curves, which could reveal the orbital period of the binary.
Fig. 1 Example light curves of accreting white dwarf transients detected by Gaia. The target on the top shows eclipses as well. The Gaia colours are derived from the BPRP spectra shown in the left hand column.

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 large data sets.

Useful references:
- CVs in transient surveys: Breedt et al 2014 MNRAS 443 3174
- Catalina Real-time Transient Survey: Drake et al 2013 MNRAS 441 1186
- Outbursts in AM\CVn stars (Helium CVs): Levitan et al 2015 MNRAS 446 391
- The Gaia Alerts stream: http://gsaweb.ast.cam.ac.uk/alerts/index
- Example catalogue construction from GDR2: Gentile Fusillo et al 2018 arXiv1807.03315
5. Searching for Extremely Metal-Poor stars in the Galactic halo with Gaia

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

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

UTO: Mike Irwin (office: 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 BP and RP 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 understand 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 SDSS or RAVE and compare expected properties with those measurable from these higher resolution spectra.

Top figures show examples of observed Gaia spectra in BP (left) and RP (right) of different spectral type stars (ESA/Gaia/DPAC/Airbus DS).
Bottom figures show the GDR2 calibrated passbands of BP (left) and RP (right), extending to the Ca H&K lines wavelength (Evans et al. 2018).
Useful references:
6. Constraining primordial non-Gaussianity with CMB lensing and large-scale structure

Supervisor I: Anthony Challinor (Room K02; a.d.challinor@ast.cam.ac.uk)
Supervisor II: Blake Sherwin (DAMTP; sherwin@damtp.cam.ac.uk)
UTO: N/A

Project summary: The aim of this project is to constrain departures from Gaussianity of the primordial cosmological perturbations using a characteristic scale dependence imprinted in the large-scale clustering of dark matter halos. This scale dependence will be probed by cross-correlating maps of the integrated dark matter distribution obtained from cosmic microwave background (CMB) lensing with tracers of the large-scale galaxy distribution, such as the cosmic infrared background (CIB).

Project description: Searching for departures from Gaussian statistics of the primordial cosmological density perturbations is a critical test of the idea of cosmic inflation. 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). In some such models, the primordial curvature perturbation \( \zeta \) can be written in the form

\[
\zeta = \zeta_G + (3/5) f_{NL} (\zeta_G^2 - \langle \zeta_G^2 \rangle),
\]

where \( \zeta_G \) is a Gaussian random field and the parameter \( f_{NL} \) quantifies the amount of non-Gaussianity. In these cases, the quadratic contribution to \( \zeta \) affects the large-scale clustering of dark matter halos, imprinting a characteristic scale dependence that can be searched for statistically (Dalal et al. 2008; see figure below). In this project, we shall primarily use a cross-correlation technique to try and minimise the impact of systematic effects in the survey maps. In particular, we shall correlate maps of the integrated dark matter distribution, reconstructed from weak gravitational lensing of the CMB, and the large-scale galaxy distribution as probed by the CIB and, possibly, other tracers (e.g., quasars). This measured correlation will be fit to models including the scale-dependence induced by primordial non-Gaussianity, with strength quantified by the parameter \( f_{NL} \).

Background: Cosmic inflation provides a compelling mechanism for generating primordial cosmological perturbations, by stretching quantum fluctuations on microscopic scales to cosmological scales. The statistics of CMB data are beautifully consistent with this mechanism for the production of perturbations, and, in particular, show that the primordial perturbations were very close to Gaussian distributed, as predicted by the simplest inflation models. However, there are many models that predict a low level of non-Gaussianity, below current CMB limits but potentially within reach of measurements with future large-scale structure surveys. Inflation models involving multiple fields can lead to a specific scale dependence in the clustering of dark matter halos on large scales (i.e., a \( 1/k^2 \) scale dependence in the halo bias, as shown in the figure below from Dalal et al. 2008).

There are several ways to look for this clustering signature, but it is generally expected that cross-correlating maps of different observables will be the most robust approach since such measurements should not be biased by additive systematic effects that are independent between the observables. Following earlier work by Giannantonio and Percival (2014), we shall cross-correlate maps of the integrated mass distribution reconstructed from lensing of the CMB (Planck Collaboration 2018) with tracers of the large-scale galaxy distribution. However, the primary
tracer we shall use is the CIB – the integrated emission from dusty galaxies, which extends to high redshift. The CIB is known to be strongly correlated with CMB lensing (Planck Collaboration 2013), and can be approximately recovered over a large fraction of the sky from the multi-frequency Planck data. Such large sky fractions are important to access the largest angular scales, where the scale-dependent clustering effect of primordial non-Gaussianity is most pronounced. Since the work of Giannantonio and Percival (2014), there have been improvements in the Planck CMB lensing maps, including better signal-to-noise and reconstruction of larger scale modes.

It is likely that the constraints derived in this project will not be competitive with those already obtained directly from the CMB. However, the approach is complementary and will have applications in future surveys where the noise levels on both the CIB and, particularly, CMB lensing maps will be considerably lower.

Project details:
[1] Survey of the literature including primordial non-Gaussianity from inflation and its effects on large-scale structure, CMB lensing, CIB and cross-correlation methodology.

[2] Produce theoretical predictions for the CMB lensing-CIB cross-correlation spectrum in the presence of scale-dependent halo bias.

[3] Produce empirically-derived models for the variance of the cross-correlation spectrum and forecast the expected precision of constraints on $f_{NL}$.

[4] Measure the CMB lensing-CIB cross-spectrum and fit parameterised theoretical models to constrain $f_{NL}$.

[5] If time allows, consider the correlation of CMB lensing with other tracers such as quasars (Sherwin et al. 2012).

[6] If time allows, consider potential astrophysical contaminants to the measured cross-correlation and estimate their impact.

We will be using CMB lensing maps from the latest Planck release (Planck Collaboration 2018) and CIB maps also estimated from Planck data (Planck Collaboration 2016). If required, quasar catalogues will come from SDSS DR14.
Figure: 3D cross-power spectra between the halo and matter density for different values of the $f_{NL}$ parameter (top), showing the effect of primordial non-Gaussianity on the large-scale clustering of halos. The ratios of the cross-spectra to a model with Gaussian primordial fluctuations is shown in the bottom panel. Figure from Dalal et al. (2008).

Skills required:
The project is a mix of analytic work, computational modelling and statistical analysis of survey maps. Standard libraries are available for many of the computational tasks, although some relatively straightforward modifications to some codes will be required.

A high level of mathematical and computational skills is required. The Part-III course Cosmology is essential, and Advanced Cosmology is strongly desirable.

Useful references:
7. Assessing the mobility of dust and gas in protoplanetary discs

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

Project summary:
This project involves modelling the evolution of dust and gas in a protoplanetary disc using a pre-existing code. The aim is to investigate the diagnostic usefulness of a quantity (relating to the relative mobility of dust and gas) which could in principle be measured by future multi-wavelength ALMA observations. The study will establish whether such measurements would be usefully constraining of the properties of dust and gas in protoplanetary discs, and, in particular, whether they may be used to estimate the local dust to gas ratio. Depending on the outcome of this investigation, there may be some scope for designing future ALMA surveys.

Project description:

Background:
Planets form from dust and gas in protoplanetary discs and thus an understanding of planet formation requires a knowledge of the distributions of dust and gas around young stars and how this evolves with time. Unfortunately, while the dust budget around young stars is easy to quantify using submm continuum emission (as provided especially by the Atacama Large Millimetre Array: ALMA), the gas reservoir is much harder to probe even though it represents the majority mass component. (Testi et al 2014). In fact, the quantity of gas in protoplanetary discs is often inferred by simply scaling the mass in dust by the gas to dust ratio in the interstellar medium (100:1).

It is however not at all clear that this approach is correct since dust and gas may not remain well mixed in discs. The extent to which dust and gas evolve in concert depends on how tightly coupled are dust grains to the background gas, this depending on both the gas density and the typical size of dust grains. (Birnstiel et al 2012). While small grains in a dense gas disc simply follow the gas as it accretes on to the star, less well coupled dust instead drifts inwards relative to the gas; in the latter case, conspicuous variations in gas to dust ratio, both locally and globally, can develop.

We have recently realized that the degree to which the dust can evolve independently of the gas is set by a dimensionless parameter (henceforth $\mathcal{R}$) which describes the ratio of the relative drift velocity of grains and gas compared with the gas inflow speed. Crucially $\mathcal{R}$ can in future be determined observationally (independently of our knowledge of the underlying gas surface density) by combining multi-wavelength observations of disc dust and estimates of the rate at which gas accretes onto the central star. The former measurements constrain the size of dust grains (and hence indirectly their drift speed) while the latter measurements (which are available for large samples of young stars) constrain the rate of inflow of disc gas. The purpose of this project is to use models to assess the usefulness of this novel diagnostic in constraining the structure and evolution of protoplanetary discs.
Project details:

We will use a model developed in Booth et al. (2017) to study the evolution of disc gas under viscous processes plus the growth, fragmentation and radial drift of dust grains. For each model disc considered it will be possible to plot its trajectory in the plane of $\mathcal{R}$ versus local gas to dust ratio. Such plots will allow the diagnostic usefulness of $\mathcal{R}$ to be judged. The student will need to consider whether there is a good case for applying for telescope time in order to obtain $\mathcal{R}$ data and, if so, how such a study could be designed.

Figure 1: Famous image of protoplanetary discs such as the richly structured disc around the young star HL Tauri below (ALMA Partnership 2015) only map the disc dust and interpreting such images requires knowledge of the transport properties of dust and gas. In this project we will assess whether a specific observational diagnostic, here designated $\mathcal{R}$, will assist in the interpretation of such images.

Skills required:
The project will require running a suite of simple simulations using an existing code that is written in Python. Small amounts of code development will be required, and thus the student will need to have, or acquire familiarity with the Python programming language.
8. Understanding the accretion of gas on to young stars

| Supervisor I: Cathie Clarke (H10, cclarke@ast.cam.ac.uk) |
| Supervisor II: Chris Tout (H61; cat@ast.cam.ac.uk) |

**Project summary:**
Young stars are observed to accrete gas from a reservoir of gas contained in their surrounding protoplanetary discs. This project seeks to understand the wealth of data acquired in recent years on how the rate of gas accretion on to young stars depends on stellar mass. Currently there is an aspect of this data which is hard to understand, namely the fact that the maximum rate of gas accretion on to low mass stars (and brown dwarfs) is surprisingly low. At first sight this suggests something unexplained about the evolution of the lowest mass stars which may shed light on their formation mechanism. However there are aspects of previous analyses of the problem which would make such a conclusion premature.

This project involves modelling how the stellar luminosity and the luminosity associated with accretion on to stars evolves with time for a variety of stellar masses, also comparing how simple models compare with observational data on accretion rates as a function of stellar mass. The aim is to discover whether such simple models can explain the observational data or if a different evolutionary scenario is required for the lowest mass stars.

**Project description:**

**Background:**
Stars form by accreting material from their natal discs. At the earliest times, the luminosity associated with this accretion ($L_{\text{acc}}$) exceeds the luminosity of the star itself ($L_\ast$). Such objects are classified as protostars. Subsequently they pass through a phase known as the `Classical T Tauri stage' where they continue to accrete from their discs but where the stellar luminosity dominates the accretion luminosity. In this phase the accretion rate declines with time until this becomes too low for the accretion luminosity to be detected. It is therefore expected that, at a given mass, an ensemble of Classical T Tauri stars should exhibit accretion rates that show a range of values, from a maximum value where the accretion luminosity equals the stellar luminosity down to a minimum value corresponding to the minimum detectable value. Such an expectation is borne out at higher stellar masses by the data shown in Figure 1 (adapted from Manara et al 2016), where the red line corresponds to the locus $L_{\text{acc}} = L_\ast$ and the grey line to the sensitivity threshold. However lower mass stars do not appear to show the same properties since their maximum accretion rates lie well below the $L_{\text{acc}} = L_\ast$ locus. This could suggest that low mass stars do not form in the same way as higher mass stars or that, alternatively, some process renders younger low mass stars with higher accretion rates undetectable.

**Project details:**
This project involves calculating evolutionary histories for young stars in which the rate of mass accretion is prescribed. This involves using stellar evolutionary models to calculate the evolution of both the stellar and accretion luminosities of the system. The aim is to discover whether the observed distribution of points in the plane of accretion rate versus stellar mass can be reproduced by such models. There will be particular interest in whether such models replicate the fact that, at mass $< 0.2 M_\odot$, the highest recorded accretion rates lie well below the line $L_{\text{acc}} = L_\ast$. Does this imply special formation scenarios for the lowest mass objects?
In order to answer this question, the student will undertake a calculation that is similar to that of Tilling et al. 2008 which however pre-dated the availability of observational data at the lowest stellar masses. This study thus did not use stellar evolutionary tracks that extended to low stellar mass and was therefore unable to address the question posed here. The present project will use new parametrisations for stellar evolution in accreting systems (e.g. Railton, Tout & Aarseth 2014) which extend to low masses.

**Fig. 1:** Observational data on the accretion rate of gas on to young stars as a function of stellar mass (adapted from Manara et al. 2016). At stellar masses \( > 0.2 \, M_\odot \) the observational data fills the entire interval between the line \( L_{\text{acc}} = L_\star \) (thick red line in the plot) and the sensitivity threshold (grey line). However there is a puzzling gap in data (i.e. an empty space below the red line) at lower masses. The purpose of this project is to discover what this data implies about possible differences in the evolutionary history of the lowest mass stars.

**Skills required:**
The project will require writing code (in any convenient programming language) to track the evolution of systems in the plane of accretion luminosity against stellar luminosity and to convert this into synthetic distributions of accretion rate against stellar mass for comparison with observations.

**Useful references:**
Tilling, I., Clarke, C., Pringle, J., Tout, C. 2008 (MNRAS 385,1530)
General references:

Tout, C., Livio, M., Bonnell, I., 2001 (MNRAS 310,360)
9. Seed formation of supermassive black holes

| Supervisor I: | Colin DeGraf (K08, cdegraf) |
| Supervisor II: | Debora Sijacki (K17, deboras) |
| UTO: | Debora Sijacki (K17, deboras) |

Project Summary: Despite their importance as astronomical probes and their role in galaxy evolution, one of the least well-understood aspects of supermassive black holes is the mechanism by which they form and the long-term effects that formation mechanism has on both the black hole and its host. This project will use a combination of cosmological simulations and analytic analysis to better understand this link and provide constraints on supermassive black hole formation and evolution.

Project Description: The goal of this project is to better understand how different formation mechanisms for supermassive black hole seeds may impact long-term black hole growth and the corresponding evolution of their host galaxies. The student will use a post-processing approach based on state-of-the-art simulations such as Illustris/IllustrisTNG to compare the populations of black holes formed from Population III stars and/or runaway interactions in dense nuclear star clusters to the commonly-used formation-independent models in cosmological simulations, as well as constraints from current and upcoming observational data.

Background: It is well understood that supermassive black holes are found at the centres of massive galaxies, and that properties of the host galaxy strongly correlate with black hole mass, suggesting a causal link between the evolution of black holes and their host galaxies (e.g. Kormendy & Ho 2013). Despite this, the initial formation of the seeds from which supermassive black holes grow remains an open question. The most commonly proposed models are massive seeds which form from direct collapse of massive gas clouds (e.g. Regan & Haehnelt 2009), light seeds which form from the remnants of the first generation (PopIII) stars (e.g. Volonteri et al. 2003), and intermediate-mass seeds which form from runaway interactions in dense nuclear star clusters (e.g. Katz et al. 2015).

Because of the uncertainty in seed formation, most numerical simulations incorporate a model which only adds a black hole well after the seed actually forms, intended to be broadly consistent with any of the models described above (e.g. Sijacki et al. 2014). However, there are several problems with this approach. Firstly, it ignores the impact that seeding may have on early black hole growth and potential long-term effects extending to late times and high black hole masses, and by construction removes any ability to differentiate between formation mechanisms. Secondly, it ignores any impact that recently-seeded black holes may have on their host, despite recent observational evidence to suggest they can be important even in low-mass galaxies (Penny et al. 2018). Although this was reasonable for earlier studies, it is becoming increasingly important to understand and accurately model seed formation, as larger computational facilities and improved observations are constantly pushing toward earlier times and lower masses, where seed formation is expected to have the strongest impact. Furthermore, seed formation can strongly impact the frequency of supermassive black hole mergers, of key importance for making predictions for upcoming gravitational wave detections from LISA and Pulsar Timing Arrays.

While some recent work has finally begun incorporating more physically motivated models for seed formation into semi analytic models (e.g. Ricarte & Natarajan 2018) and hydrodynamic simulations (e.g. Habouzit et al. 2016), cosmological simulations still consider only a single formation model and thus do not provide comparisons between mechanisms. This project will use a unique post-processing approach developed by DeGraf and Sijacki to efficiently compare different seed models to study their impact on a wide range of observables to help constrain seed formation models, better understand current and upcoming observations, and improve future cosmological simulations.
**Project details:** This is a theory-based project using a combination of numerical simulations and analytic analysis.

- Initially, the student will familiarize themselves with the black hole output files from the Illustris simulation.
- Using the method previously developed in DeGraf & Sijacki, the student will re-calculate the growth of the black holes in the Illustris simulation for a new seeding model, forming from PopIII stars (i.e. seeding a subset of black holes from the original simulation).
- Using the population of recalculated black holes, the student will be in a position to compare a wide range of observables at different redshifts to current observational data and place constraints upcoming surveys/observations can make, e.g.:
  - Mass and luminosity functions
  - Eddington Rate Distribution Function
  - Black hole – galaxy scaling relation
  - Black hole clustering
  - Black hole merger rates
  - Including frequency of gravitational wave signals detectable by LISA and/or Pulsar Timing Arrays
- In the second part of the project, the above analysis can then be repeated for the seed formation from nuclear star clusters rather then PopIII stars.
- Furthermore, the above analysis can be applied to the IllustrisTNG simulations, a set of followup simulations using improved physics models and including an equivalent simulation box (TNG100) and a much larger volume run (TNG300), scheduled to go public on December 7, 2018.
- Particularly ambitious students can apply the same post-processing analysis to zoom-in simulations (run by DeGraf). These zoom-in simulations will include separate runs for each seed model, allowing for explicit comparison between the post-processing predictions and runs which directly incorporate the given seed model, and thus quantifying the scales at which the post-processing predictions are reliably accurate.

**Skills required:** As a primarily computational project, students should be comfortable with programming in a language suited to analysis such as Python or IDL (but any language is acceptable). No prior familiarity with simulations will be needed, however. Most analysis will involve black hole output files which can be provided as plain ASCII text, or a structured SQL database. If further simulation analysis is desired, data access and example reading/analysis scripts are available at [http://www.illustris-project.org/data/](http://www.illustris-project.org/data/).

The Part II lecture courses “Astrophysical Fluid Dynamics” and “Physics of Astrophysics” are desirable.

**Useful references:**
General references:

*Illustris simulation data and access info:* Nelson et al., 2015, Astronomy & Computing, 13, 12


*Black hole seed formation reviews:* Latif M. & Ferrara A., 2016, PASA, 33, 51
10. The heating and cooling cycles in solar active region plasma

Supervisor I: Giulio Del Zanna, F1.05, gd232@cam.ac.uk
Supervisor II: 
UTO: George Efstathiou

Project summary:
The focus of this project is to provide observational evidence on the heating and cooling cycles in solar active region (AR) loops. A clear understanding of the thermal distribution in coronal loops and how it evolves (i.e. the heating and cooling cycle) reveals information regarding the heating mechanism.

Project description:
Since 2010, we have a huge amount of data to be explored: high-cadence (12s), high-resolution (1 arc sec) EUV images of the solar corona from the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) in six coronal bands, sensitive to a range of temperatures.
As described in Del Zanna (2013), it is possible (although not trivial) to obtain temperature information using these bands, and a knowledge of the atomic data.
The bulk of the project work will be to run inversion codes, some of which are now very fast (e.g. AIADEM, Cheung et al. 2015), to measure the evolution of the temperature of coronal loops. By measuring loop lengths and cross-sections it will also be possible to estimate the cooling times of the main processes, by radiation and electron thermal conduction. Comparing these times to the observed lifetimes of the structures will provide information on the cooling.
The project has ample flexibility, depending on the interest of the student. For example, X-ray imaging from the Hinode X-Ray Telescope (XRT), as well as EUV spectra from Hinode EIS, and magnetic fields from SDO HMI could in principle be used as additional information, if time allows.

Background:
The solution to the long-standing problem of solar coronal heating remains elusive despite major advances in observational and theoretical capabilities over the last few decades. The most obvious features of the solar corona are active region loops, connected to strong photospheric magnetic fields in sunspot and plage. The cores of active regions contain warm loops [T = 1 MK], fan loops [T < 0.8 MK], and hot loops [T = 3 MK].

The most widely accepted theory for the coronal heating assumes that nanoflare storms occurring in the corona heat the plasma to temperatures higher than 3 MK, with subsequent cooling to form the 3 MK loops (see, e.g. Cargill 2014). Other theories, such as the dissipation of Alfvén waves (e.g. Van Ballegooijen et al 2011) also predict high-temperature plasma heated by short-lived events. The presence of this hot plasma above 3 MK has been, however, a matter of much debate.

It is also unclear whether the warm loops are related to the hot loops, in particular if those in the cores are a product of the cooling of the hot loops.
The cool emission that is observed in the AR cores is often interpreted in the literature as the product of the cooling of the hot emission (see, e.g. Viall and Klimchuk 2012), but the evidence is not clear, as it is often difficult to see the thermal evolution of a single loop, as it occurs during a flare (e.g. see the textbook case in Del Zanna et al. 2011). Resolving this issue observationally is a challenge, as it is normally impossible to trace out any structure with temperatures above 1 MK.
that was previously in the same location as the cool emission. This is due to the unresolved nature of the emission at coronal temperatures above 1.5 MK. The issue whether the cool loops are isothermal in their cross-section has also been a matter of debate. Our view is that they are nearly isothermal (cf. Del Zanna 2003, 2013), but in the literature other views can be found (cf. Schmelz et al. 2013).

Project details:

The student will start by searching the SDO and Hinode databases to identify a few good active regions to study in terms of their evolution. The searches are mostly web-based (Helioviewer and databases) and relatively straightforward, as is the data download. The aim is to select a few cases of quiescent ARs with as many multi-wavelength observations as possible.

![Images of solar active region loops, as seen in two SDO/AIA EUV bands, sensitive to different temperatures. The 171 A shows the cool and warm loops, the 195 A has contributions from higher temperatures.]

We will focus first on SDO AIA images, select a field of view (cf. image above), correct for solar rotation, then create movies and light curves of selected loops in the various bands. Then, run inversion programs to find the temperature structure of the loops and how it evolves. Cooling times will be estimated measuring the sizes of the loops, using the measured temperatures and estimates of densities.

The analysis of the data will involve running SolarSoft (IDL) for data calibration and co-alignment, which is available on DAMTP computers (a DAMTP unix account will be provided). The programs could also be installed on a laptop, but the amount of data to be processed is large.

The project will involve some IDL programming, to select spatial and temporal regions, to plot lightcurves, and to run several programs. Note that IDL is very similar to Python.

The student will also learn the basics of the atomic data which we provide (CHIANTI, see Del Zanna+2015) for the analysis of astrophysical spectra from plasmas, not just solar data.
Skills required:
- basic unix commands, see e.g.
  https://things.maths.cam.ac.uk/computing/linux/
- basics of IDL programming (variables, data types, structures, functions and procedures, input/output and simple 1-D plots), which can easily be found online.

Useful references:
- Helioviewer: https://www.helioviewer.org/
- Documentation about AIA: https://www.lmsal.com/sdodocs/
- SDO AIA data: http://www.lmsal.com/get_aia_data/
- Hinode data: http://sdc.uio.no/search
- CHIANTI data: http://chiantidatabase.org
- AIA Temperature analysis: http://tinyurl.com/aiadem

General references:
- Del Zanna, Part III lecture course (Lent term) on High energy radiative processes in astrophysical plasma
- Cargill 2014: http://adsabs.harvard.edu/abs/2014ApJ...784...49C
- Del Zanna 2013: http://adsabs.harvard.edu/abs/2013A%26A...558A..73D
- Del Zanna+2015: http://adsabs.harvard.edu/abs/2015A%26A...582A..56D
- Viall and Klimchuk 2012: http://adsabs.harvard.edu/abs/2012ApJ...753...35V
11. Moths to a flame - Clustering of z~2 galaxies around luminous QSOs

Supervisor I: Catrina Diener (O24, cd623)

Supervisor II: David Murphy

UTO: Mike Irwin

Project summary:
This project explores whether high luminosity QSOs at a redshift of 2 serve as probes for proto-clusters of galaxies, or if they are (as controversially discussed) generally found in an intermediate density environment. Either answer will lead to a better understanding of where the earliest large-scale structures form in the universe, and how they evolve to become today's galaxy groups and clusters.

Project description:
At a redshift of 2, the universe (a quarter of its present age) experienced a peak in the volume-averaged Star Formation Rate coinciding with an era of significant mass assembly in proto-clusters of galaxies. At this epoch, the progenitors of today’s galaxy clusters can be observed and identified, but correctly determining the galaxy membership of these nascent structures is very observationally challenging due to poor contrast with respect to the average galaxy density at these redshifts.

Controversy surrounds whether the most luminous QSOs are beacons of high density environments (progenitors of today's galaxy clusters) or endemic to lower mass environments (progenitors of today’s galaxy groups). At the same time, computer simulations of large-scale structure suggest that, across over two orders of magnitude in QSO luminosity, the luminosity (and hence mass) of a QSO has no connection to the environment it lives in.

In this project, we test these hypotheses via Near-IR observations (ESO VLT, LCO Magellan) of Hα emitting galaxies around a sample of z~2 QSOs. The aim is to identify these galaxies via the “narrowband excess” technique, study their clustering around the parent QSO, and determine galaxy properties as a function of the environment. These results will be compared to existing surveys that performed clustering studies in higher-mass environments (proto-clusters) and the field.
Background:

In the last few years, great strides have been made in our understanding of galaxy formation and evolution throughout cosmic time. It is believed that environment plays an important role in forming galaxy properties and most critically in the control of star-formation. At 2<z<6 the cosmic star-formation rate density rises steeply, accounting for a rapid mass build-up in these early galaxies. Understanding how this depends on their environment is a key building block to our understanding of early galaxy evolution.

At low redshift (z~0) a galaxy’s environment is reasonably well defined: the ladder of different environments starts with field galaxies which occupy their own dark matter halo and are endemic to a rather low mass surrounding. The next rung on the ladder is groups of galaxies, comprising a few to a few tens of galaxies that are gravitationally bound. Finally, galaxy clusters represent the most massive structures in the Universe, with several 100 to 1000 members and are home to a number galaxy shaping processes. At the very largest scales, galaxies and clusters of galaxies are distributed in a cosmic web permeated by large voids.

Whilst low-redshift structures of galaxies are easily identified, their high redshift counterparts consist of a far more diverse and somewhat ill-defined population. A proto-cluster is generally thought of as a structure of galaxies which by today’s Universe will evolve into a galaxy cluster - it therefore represents the “early childhood” of today’s clusters. In the same way we would define a proto-group. Understanding the early childhood of today’s structures is an important puzzle piece to our understanding galaxy evolution in the context of environment.

Observationally it is very challenging to detect these proto-structures. Often “beacon” galaxies are used as tracers statistically likely to be at the center of an emerging cluster or group. These beacon sources tend to be embedded in high-mass dark matter halos. One such type of beacon is high redshift radio galaxies, which are known to often be surrounded by a proto-cluster. On the other hand, high luminosity radio-quiet QSOs have been suggested as probes of proto-clusters. However the observational evidence is mired in controversy, with some authors finding QSOs in dense environments whilst others don’t. At the same time simulations suggest that QSOs are situated in intermediate environments (“proto-groups”) and that this statement is true when spanning two orders of magnitude in QSO luminosity. This project will answer this question with a self-consistent data-set that probes the z~2 environment of luminous QSOs and that is complimented by a similar data-set for radio galaxies and field galaxies.
Skills required:

This is an observational project geared towards students that would like to gain experience in treating and analysing larger cosmological datasets. The student is expected to be familiar with PartII cosmology. They will need to be comfortable in coding in a language like Python, Matlab or R. During the project the student will be expected to get up to date with astronomical data analysis tools such as SExtractor, DS9, topcat, scamp, etc (any prior knowledge is an asset but not a requirement).

This project is ideal for a student with interests in observational cosmology that is keen on learning state-of-the-art data analysis techniques and tools. From a first look at the data, there is a considerable discovery potential that may spawn follow-up investigations and observations.

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

https://arxiv.org/abs/1305.2199

https://arxiv.org/abs/0805.2861

https://arxiv.org/abs/1606.07452

https://arxiv.org/abs/1506.08835
12. Redshift Space Distortions: Constraints on $\sigma_8$

Supervisor I: George Efstathiou (K15) gpe@ast.cam.ac.uk
Supervisor II: Steven Gratton (K7) stg20@ast.cam.ac.uk
UTO: N/A

Project summary: The aim of the project is to use recent measurements of redshift space distortions (RSD) from the Baryon Acoustic Oscillation Spectroscopic Survey (BOSS) to constraint the amplitude of the matter fluctuations at the present day (quantified by the parameter $\sigma_8$).

Project description: Galaxy peculiar velocities introduce perturbations in the Hubble law relating recession velocity to true distance. This effect can be measured via the anisotropy of galaxy clustering in galaxy redshift surveys, since peculiar velocities distort distances along the line-of-sight, but not in the transverse direction. The RSD effect has been measured accurately in the recent BOSS DR12 series of papers, summarized by Alam et al. 2017. The amplitude of the fluctuations is usually quantified by the rms fluctuation in spheres of radius 8h$^{-1}$ Mpc, $\sigma_8$. (Here h is the Hubble constant $H_0$ in units of 100 km/s/Mpc). However, RSD do not directly constrain $\sigma_8$, but instead constrain the combination $f\sigma_8$, where f measures the logarithmic derivative of the growth rate of linear fluctuations. In this project, the idea is to use observational data to constrain the background cosmology independently of the form of dark energy. Solution of the perturbation growth equations will fix the quantity f. We can then assess whether there is any exotic dark energy model that can account for the difference between weak lensing measures of $\sigma_8$ (DES collaboration 2017) and the value inferred from recent observations of the cosmic microwave background (Planck Collaboration 2018) assuming the standard $\Lambda$CDM cosmology.

Background: With the high precision measurements of the cosmic microwave background (CMB) from Planck, we have tight constraints on the Universe at high redshifts. As far as we can tell, the CMB data are well described by a six-parameter $\Lambda$CDM model. In this model, the dark energy is a cosmological constant. However, dark energy becomes dynamically important only at late times (redshifts z<1). The CMB is insensitive to late time physics and therefore does not constrain the nature of dark energy. To do this, we need to use other techniques. At the moment, the situation is confused. There are some indications from weak galaxy lensing that the fluctuation amplitude at z~0.5 is lower than expected in the $\Lambda$CDM model. RSD measurements have been made at similar redshifts. In this project, we want to see whether we can find a ‘model independent’ way of relating RSD to galaxy weak lensing measurements. It is likely that current data will not give a conclusive result. However, the techniques developed may have applications to future large lensing and galaxy redshift surveys.

Project details:
[1] Survey of the literature including RSD, baryon acoustic oscillations (BAO), CMB and weak galaxy lensing.
[4] Derivation of the logarithmic growth of perturbations rate from step [3] and comparison with the expectations of $\Lambda$CDM.
Comparison of RSD constraints with results of weak gravitational lensing from the KiDS survey (Hildebrandt et al., 2017) as in the Figure below (from Efstathiou and Lemos, 2018). This figure is restricted to the $\Lambda$CDM and needs to be generalised to more general models of dark energy.

Forecasts for future weak lensing and galaxy redshift surveys.

Skills required:
This project is quite demanding. Referring to the numbers above:
[2] Requires Monte-Carlo-Markov-Chain (MCMC) analysis of BAO and supernova data. This is probably best done in python using the emcee sampler.
[3] Requires analytic and numerical skills to solve the perturbation equations.
[4] Requires more MCMC runs using the results of [2].

A high level of mathematical and computing skills are required. You should have taken courses in cosmology and general relativity.

Useful references:
Planck Collaboration, 2018, arXiv:1807060209
13. Dynamical Models of Galactic Bars

Supervisor I: N W Evans (H50) nwe@ast.cam.ac.uk

Supervisor II: J. L. Sanders (H33) jls@ast.cam.ac.uk

UTO: NW Evans

Project description:

Observational evidence from the surface photometry of barred galaxies suggests that there exists a dichotomy (Sellwood & Wilkinson 1993). In early-type galaxies (SB0, SBa), the surface brightness falls slowly along the bar major axis. Occasionally, the surface brightness is nearly constant to the end of the bar.

In late-type galaxies (SBb, SBc), however, the light profiles are strongly falling exponentials along the major axis. For example, Elmegreen et al. (1996) took infrared band observations for a sample of barred galaxies across all Hubble types. They confirmed that early-types have flattish light profiles, whilst late-types have exponential profiles. Across the bar, the profile appears to be Gaussian.

The aim is to build potential-density pairs of triaxial rotating bars, which have an exponentially declining profile along the major axis, and Gaussian profile along the intermediate and minor axes. The models can be used to provide fits to N-body bars or to the surface photometry of bars and to study the orbital structure as a function of pattern speed.

Depending on progress and interests of the student, the project can be extended to study bar evolution in numerical experiments or to examine the effects of the Milky Way bar on nearby stellar streams in the inner Milky Way Galaxy.

Project details:

Long & Murali (1992) introduced a clever algorithm to produce bar-like densities. It convolves an underlying spherical or axisymmetric density with a needle-like density, or weight function. Long & Murali (1992) and William & Evans (2017) used a constant needle density and this tends to produce bars with flattish profiles along the major-axis suitable for early-type galaxies. If instead an exponential weight function is used, then this produces models with exponential major axis profiles and Gaussian cross-sections.

The first step is to use this insight to produce families of bar models suitable for late-type galaxies. These models should be compared to the photometry of late-type bars and fitted to the end-points of N-body experiments. This will produce simple, flexible and realistic bar models. The next step is to understand the orbital structure of the bar as a function of the pattern speed (e.g., by orbit integrations, Poincare section and bifurcation plots). This is similar to the exploration in Williams & Evans (2017) for early-type bars.

If progress is good, the project can be extended to build (with Made-to-Measure) models of the bars and study their evolution. Or, the models can be used to mimic the Galactic bar and study the effects of a realistic bar on stellar streams in the inner Galaxy (e.g., Hattori et al 2017).
Requirements

This project will require mathematical skills to build the analytic bar models. Proficiency with e.g., Mathematica would be useful. The remainder of the numerical work requires proficiency with python or C.

It is suitable for students who have attend a final year course on Principle of Dynamics (e.g., in Mathematics Part II) or its equivalent. Familiarity for example with Lagrangian or Hamiltonian mechanics is needed.

Useful references:


General references:

Binney J., Tremaine S. 2008, Galactic Dynamics, Princeton University Press (especially chaps 2 and 3)
Goldstein H. 1980, Classical Mechanics, Addison-Wesley (especially chapters on Hamiltonian mechanics)
Sellwood, J.A & Wilkinson 1993, Reports on Progress in Physics, 56, 173 (Review of the subject, including both theoretical and observational aspects).
14. The structure and properties of massive stellar envelopes: convection, radiative transport, and the roles of opacity and ionization

| Supervisor I: Avishai Gilkis (Room H35, agilkis@ast.cam.ac.uk) |
| Supervisor II: Christopher Tout (Room H61, cat@ast.cam.ac.uk) |
| UTO: Christopher Tout |

**Project summary:**
The goal of the project will be to understand the stellar properties which give rise to the complex envelope structure in massive stars.

**Project description:**
The student will learn to use a stellar evolution code and evolve massive stars until the end of core helium burning. The student will then analyse in detail the various physical properties of the stellar envelope. The project can be expanded to investigate the dependence of the envelope structure on the evolutionary stage and the initial stellar properties.

**Background:**
Neutron stars and black holes are generally considered to be formed through the collapse of an iron core of a massive star, with a mass initially above about eight times that of the sun. These stars typically have convective cores and radiative envelopes while on the main sequence, and during advanced evolutionary stages develop convective envelopes. Stellar evolution models show that the higher range of initial masses leads to somewhat more complex envelope structures, with several layers alternating between convective and radiative energy transport. While the core-collapse progenitor stars in this higher mass range are rarer than typical core-collapse supernova progenitors, they are likely the predominant origin of stellar mass black holes which are observed in detections of gravitational waves, and therefore the understanding of their structure and evolution is significant. Specifically, synchronization of the stellar spin to the orbital period through tidal torques depends on the envelope properties, with implications both for subsequent evolutionary stages and the spin of the black hole formed during core collapse. A qualitatively similar physical envelope structure has been studied by Cantiello et al. (2009), although for hot main-sequence stars, in which the convective parts of the envelope were found to be extremely small in magnitude. Cantiello et al. attributed the occurrence of convective zones within the main-sequence radiative envelope to opacity peaks due to ionization of iron and helium. This project is focused on later stellar evolution stages, where the massive star has already expanded substantially.

**Project details:**
The project is computational in its nature, and will consist of the following:
* Learn to use a stellar evolution code.
* Understand and model the evolution of massive stars from the zero-age main sequence until the end of helium burning in the core.
* Study the envelope properties of evolved massive stars, such as opacity, temperature, ionization of helium and iron, the adiabatic gradient, and stability against convection.
Figure 1: Convective velocity (calculated according to the mixing-length theory) relative to the local sound speed $c_s$ as function of radial coordinate within an evolved massive star. This quantity is defined only for convective regions. The vertical dashed line marks the edge of the stellar core. The model represents a blue super-giant star with a mass of $23 M_\odot$. The initial mass was $35 M_\odot$, but about a third of the stellar mass was lost through winds.

**Skills required:**
Some knowledge of stellar evolution is essential. The part-II course on Structure and Evolution of Stars suffices but the part-III course is desirable.

**Useful references:**

**General references:**
15. Collisions of neutron stars and red giants: stellar properties at collision, occurrence rates, and sensitivity to supernova dynamics

Supervisor I: Avishai Gilkis (Room H35, agilkis@ast.cam.ac.uk)
Supervisor II: Christopher Tout (Room H61, cat@ast.cam.ac.uk)
UTO: Christopher Tout

Project summary:
The goal of the project will be to estimate the occurrence rate of neutron stars merging with red super-giant stars using a rapid stellar evolution code.

Project description:
The student will learn how to use a rapid stellar evolution code to evolve representative synthetic populations of neutron star merger progenitor systems. The student will then analyse the different evolutionary channels leading to tight neutron star binary systems, with emphasis on systems where a neutron star went into a common envelope. Systems which result in merged stars, such as Thorne-Żytkow objects (a red giant star with a degenerate neutron core), are also of interest. The project can be expanded to study the effect of different metallicities, and different assumptions on the velocity of newly-formed neutron stars.

Background:
The merging of two neutron stars has been recently observed for the first time both in gravitational waves and the electromagnetic spectrum, and is also generally thought to lead to short-duration gamma-ray bursts. The long-term evolution leading to the merging is highly uncertain, with one of the least understood phases being that of common envelope evolution, when one star is engulfed by the envelope of its companion. The result of the common envelope phase is either a binary star system with a reduced separation, after the envelope has been dispersed, or a single merged star, if the orbit inside the common envelope shrinks sufficiently. Whether the common envelope phase is reached with the companion being a neutron star or a main sequence star depends on the initial parameters of the system, mostly the stellar masses and the orbital separation. Another important process in the evolution is the abrupt change in orbital parameters during a supernova event, in which the neutron star receives a high kick velocity during formation, owing to asymmetries in the supernova mechanism. Depending on the velocity orientation and magnitude, the binary system might become unbound. If the two stars do not merge during a common envelope phase, and neither supernova event unbinds the system, a binary neutron star system can form. It has likely passed through one or more common envelope phases, one of which might have involved a neutron star entering the envelope of a massive red super-giant star. Owing to the very high energy release during accretion on to a neutron star, several theoretical scenarios suggest an energetic supernova-like outcome from accretion on to a neutron star inside the envelope of a red super-giant star, although the exact nature and occurrence rate of such interactions are not known.

Project details:
The project is computational in its nature, and will consist of the following:
* Learn to use a population synthesis code
* Understand and model the evolution of binary stars from the ZAMS until neutron star formation.
* Explore the parameter space leading to NS-RSG mergers and NS binaries.
* Vary the assumptions on NS kick velocities and see the effect on the resulting rates.
Figure 2: Binary evolution, where NS is neutron star, BH is black hole, TZO is Thorne-Żytkov object, and SN is supernova. From Chevalier (2012).

Skills required:
Some knowledge of stellar evolution is essential. The part-II course on Structure and Evolution of Stars suffices but the part-III course is desirable.

Useful references:

General references:
### 16. Are the first stars hiding behind later pollution?

**Supervisor I:** Gerry Gilmore (H47, gil@ast.cam.ac.uk)  
**Supervisor II:** Clare Worley  
**UTO:** Gerry Gilmore

| **Project summary:**
| Extremely metal-poor/zero metal stars formed very early in the Universe. If any formed with mass below 0.8Msun they will survive today. They are proving hard to find. A possible explanation is that initially zero-metallicity low mass stars were polluted by accretion of later enriched ISM, and so now seem to be simply very metal-poor. Recent cosmological simulations have considered the pollution option, and some early stellar evolution studies did as well. The distribution of chemical elements with mass-number is a very strong function of time, so very early pollution would lead to quite different elemental abundance distributions than would later pollution. The pollution pattern, if any, may be sufficiently distinctive to be detectable even in known and studied metal-poor, rather than yet to be found zero-metal stars. |

| **Project description:**
| The idea here is to put together modern knowledge of chemical element transport in low mass stars, allowing for the uncertainties, with models of the different timescales of creation of the various families of chemical elements (alpha-process, r-process, s-process, i-process, ...), and observed element distributions in very low abundance stars. And see what we find. |

| **Background:**
| The oldest stars show the history of chemical element creation up their formation. The very earliest stars have not been found. Accretion of enriched material later in their life may be hiding these stars. |

| **Project details:**
| Take available models of element diffusion in very old stars and their uncertainties to see what changes to the at-formation stellar abundance pattern are anticipated now. Take the various element ratio patterns expected vs time from nucleosynthesis to summarise how element patterns should change with time. Combine the two and compare to observed very old stars to search for anomalies which indicate accretion/pollution signatures. |
Figure from Johnson 2015 showing that the distributions of some elements (Zn, Ti) may contain interesting new information compared to available models. The solid line is a model of accretion from the ISM affecting stellar initial abundances.

Skills required:
Stellar evolution course material will be good background. Mostly this requires collection of data and plotting, and searching available metal-poor star dBases.
The JINA database has a very easy interface http://jinabase.pythonanywhere.com/
The SAGA database is also good and easy http://sagadatabase.jp/

Useful references:
Chemical element transport in stellar evolution models, Salaris & Cassisi, 2017 arXiv:1707.07454
Chemical enrichment of stars due to accretion from ISM Shen etal 2017 MNRAS.469.4012
Chemical signature of surviving POPIII stars Johnson 2015 MNRAS 453.2771
17. Were Eddington and Dyson correct in 1919?

Supervisor I: Gerry Gilmore H47 gil@ast.cam.ac.uk
Supervisor II: Gudrun Pebody, Anais Gonneau, Clare Worley, Anna Hourihane,
UTO: Gerry Gilmore

Project summary:
Gravitational light-bending measured during the 1919 May 29 eclipse provided a key test of General relativity, and made Einstein famous. While generally accepted, the eclipse measurements have sometimes been claimed as biased, in spite of lack of any evidence. At the time only simple by-hand astrometric fits were possible. For the eclipse centenary this project will re-analyse the published Eddington/Dyson star x-y positions using modern public-domain astrometric codes. The goal will be to investigate the true measurement errors and range of solutions, and compare with Eddington’s by-hand solution.

Project description:
In November 1919 Eddington and Dyson announced a result reported as a headline in the London Times of 7-11-1919 as “Revolution in Science/ New Theory of the Universe/ Newtonian Ideas Overthrown”. That proved an understatement. The eclipse results were derived by measuring stellar positions during a Solar eclipse, and comparing with comparison plates of the same sky area.
All the x-y position were published, though not in a trivial way. This project will take the published coordinates, fit them with a modern code, and explore two things. One – are the measuring errors consistent with the estimates of the time; two – what ranges of solution space are viable subject to varieties of data clipping.
If time allows the same analysis will be applied to the three expeditions to a 1922 eclipse which confirmed the result.

Background:
The 1919 eclipse made Einstein, GR, and Eddington famous. The result was adopted very widely and rapidly, although famously obscure. The history of the reception of GR is complicated by racism, politics, and incomprehension, and is an interesting story in its own right (Kennefick 2009). For unclear reasons (to us) a fashion arose in the Philosophy of Science community in the 1980s that the 1919 result lacked the statistical weight to support the conclusion. Claims of bias against Eddington arose, and remain surprisingly widely believed by those who have failed to look at the literature.
As part of the centenary of 1919, this will be (so far as we know) the first modern computer era re-reduction of the original published stellar coordinates. What shall we find?

Project details:
Stellar coordinates from each relevant photographic eclipse plate are published in Dyson, Eddington & Davidson 1920. Some careful text reading will be required to understand coordinate scales, but all information is there. These coordinates will be fed into available astrometric codes – eg WCSTools, Astrometry.net, or others. Some experiments will be needed with errors, data clipping etc to probe robustness issues and error bars.
Errors can be compared with earlier studies of Cambridge astrometry which led to the first Hertspung Russell diagram (Hinks & Russell 1905)
Straightforward statistical testing can follow.
Skills required:
Basic computing to manage interfaces, some statistics knowledge. Mostly this requires common sense and care with units and scales.

Useful references:
Dyson, Eddington & Davidson Proc Roy Soc A 220 291-333
Kennefick Physics Today March 2009 pp37-43
Hinks, A, Russell, H.N. 1905 MNRAS LXV pp775-787
Campbell, W.W. 1923 PASP 35 11

General references:
Harvey, Observatory Magazine, 99 195 1979
tdc-www.harvard.edu/software/wcstools/publications/wcstools.adass98.html
astrometry.net/
http://star-www.dur.ac.uk/~pdraper/gaia/astromcal/index.html is a baby tutorial
18. Variability in Star Formation Sites: A Search for FU Orionis stars

| Supervisor I: Carlos Gonzalez-Fernandez (cgonzal@ast.cam.ac.uk, APM-5) |
| Supervisor II: Simon Hodgkin (sth@ast.cam.ac.uk, H39) |
| UTO: Mike Irwin (mike@ast.cam.ac.uk, APM-1) |

**Project summary:**

FU Orionis stars are a rare type of variable that correspond to the last stages in pre-main sequence stellar evolution. Little is known about the physics of these stars, in large part due to their scarcity. In this project we aim at finding a new sample of them in the Magellanic Clouds.

**Project description:**

Using 8 years of near infrared archival imaging data for the Magellanic Clouds, we will conduct a systematic search for FU Orionis stars in several, if not all, of the large stellar formation regions of the Large and Small Magellanic Clouds. All the known objects in this group have been detected in our galaxy, and therefore extending the samples to other environments will help us understand their properties and evolution.

**Background:**

Before they enter the main sequence, stars often show variations in brightness. The evolution and physics of young stellar objects (YSO) are complicated, as they involve the interplay of an accretion layer, a disc, surface irregularities in the star being formed and the effects of magnetic fields. These yield several patterns of variability; among others, periodic low amplitude variations due to rotation and starspots, short outbursts related to episodic accretion onto the star, and dips in brightness due to disc eclipses.

One type of YSOs of particular interest are FU Orionis type stars (known as FUOrs); these are pre-main-sequence stars that have already shed most of their accretion envelope and are in the last stages of YSO evolution. These stars are characterized by sudden large increases in brightness, reaching 5 o 6 magnitudes, that last for several years (see Fig. 1); these episodes are related to a major increase in the rate of transfer from an accretion disc, for which the reason (or even whether this is actually the case) is not well understood. These objects are interesting as they can shed light on stellar accretion and the way stars acquire their initial mass. One of the problems studying FUOrs is that few of them are known, about 30, all of them in our Galaxy [1].

The aim of this project is to correct this situation.

**Project details:**

The VISTA telescope (http://www.vista.ac.uk/) is a near infrared (NIR) facility dedicated to survey science, whose data are being reduced at CASU. One of the main observational programs undertaken by VISTA is VMC, that targets the Magellanic Clouds [3], has taken images of several massive stellar formation regions, over a 8 years span. We will use this data set to look for FUOrs in the Magellanic Clouds.

The NIR offers the advantage of a higher penetration into interstellar material, crucial for this endeavour as we expect FUOrs to be surrounded still by leftover material from their parental
cloud. Also, the stellar density of these formation regions is high, so standard image analysis techniques as aperture photometry do not perform well. For this, we will use higher precision tools such as difference imaging, that allows us to match the point spread function (i.e. the effective spatial resolution) of two images taken at different times (in this case, several years apart) and make measurements directly onto the difference image, eliminating many of the systematics and allowing us to easily detect photometric variability.

![Figure 3 Light curve of V2493 Cyg, showing the brightness increase associated with FUOrs [2](image)](image)

Succinctly, the project will consist of these steps:

- Selection of candidate stellar formation regions and most appropriate images from the VMC survey to perform first analysis, for example selecting those with the best seeing.
- First catalogue of variable candidates, identification of interlopers, like foreground stars or other type of variables. The chance of serendipitous science is high, and some of these other variables will be interesting too, like blue long period variables, that correspond with very massive OB stars.
- Reconstruction of full light-curves and scientific analysis. Once bona fide FUOrs are identified, a full VISTA lightcurve can be constructed by using all the available data. Some of these will be the first FUOrs to be identified in another galaxy and will open the door to interesting analysis like abundance as a function of metallicity, relative number with respect to other populations, etc.
- Depending on the results obtained up to this point, it is possible to extend the project onto massive stellar formation regions in the Milky Way, that are also being covered by VISTA under the VVV survey [4].

Skills required:

Given the practical nature of this project, students should be comfortable with some programming/scripting language, such as Python or IDL, and some familiarity with Unix based systems would also be helpful. Knowledge of stellar evolution (as in the Part II course) will make the project more enriching.
Useful references:
- A Near-infrared Spectroscopic Survey of FU Orionis Objects, Connelley & Reipurth, AJ 2018
- The VISTA ZYJHKs photometric system: calibration from 2MASS, González-Fernández et al., MNRAS 2018

General references:
[2] Optical light curves of FUor and FUor-like objects, Semkov, Peneva, Stoyanka & Sunay, IAUS 2017
19. Point Source Masking in Planck

<table>
<thead>
<tr>
<th>Supervisor I: Steven Gratton (K07, <a href="mailto:stg20@cam.ac.uk">stg20@cam.ac.uk</a>)</th>
<th>Supervisor II: George Efstathiou (K15, <a href="mailto:gpe@ast.cam.ac.uk">gpe@ast.cam.ac.uk</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTO: George Efstathiou</td>
<td></td>
</tr>
</tbody>
</table>

**Project summary:**

The student will investigate the point-source masking of Planck Microwave Sky Maps, with a view to deepening understanding both of what is being masked and of the masking procedure itself.

**Project description:**

The student will learn about power-spectrum-based analysis of cosmic microwave background maps, and develop an appreciation of the complications induced by both galactic and extragalactic foreground emission.

Using the second Planck Catalogue of Compact Sources (PCCS2/2E), the student will construct a series of point source masks using a variety of criteria and investigate their effects on the power spectra of the maps. This should lead to an increase in understanding of both the physical properties of what is being masked and of potential statistical influences of the masking procedure on the cosmological analysis.

The student may go on to perform parameter analyses on the resulting spectra using the publically available CosmoMC software in order to quantify any changes to cosmological inferences coming from changes in the masking.

**Background:**

The Planck Satellite has made maps of the microwave sky at multiple frequencies, both in temperature and polarization. A major contributor to these maps is the cosmic microwave background, emitted only a few hundred thousand years after the big bang and from whose statistics we can deduce much about the Universe (see P18).

There are however additional sources of radiation. At higher frequencies, vibrating dust grains account for much of the diffuse galactic emission. The properties of this dust emission appear to be so regular across the sky that it can be removed to high accuracy up until close to the galactic plane. The data very close to the plane is then simply discarded by the application of a diffuse galactic mask.

In addition, there appear to be “compact regions” of dust that do not emit so uniformly. Furthermore, there is emission from extragalactic sources, such as dusty star-forming galaxies. Both types of sources appear effectively as point-like to Planck. For a cosmological analysis their effects are mitigated by the application of point-source masks to ignore such regions of the sky. Residual unmasked emission is then modelled.

The point source masks are typically constructed from point-source catalogues, which have been produced internally to Planck by a frequency-by-frequency analysis of the Planck maps themselves. As for example the noise in the maps varies with sky position, the details of the sources masked can actually vary across the sky. In addition, some of the sources might
potentially be slightly extended, or only detectable at certain frequencies. One has to make choices about which sources to include in the masks or not. This project aims to understand in some detail any consequences of such decisions for the cosmological interpretation of Planck data.

Project details:

The student will begin by downloading the PCCS2/2E and constructing a variety of masks exploiting the wealth of information contained in the catalogues. The plot below for example illustrates some of the sources appearing in the catalogues at selected frequencies:

![Image of sources appearing in the catalogues at selected frequencies]

The student will construct power spectra of Planck maps with the various masks applied and so develop an increased understanding of both the nature of the objects masked and of influences of the masking procedure itself on results.

Thus it may be possible to produce an improved set of point source masks for the analysis of Planck along with a suitable model of residuals left in the power spectra.

As Planck measures both temperature and polarization, there is scope to investigate polarized point source emission also.

The student may go on to investigate the cosmological consequences of the application of such masks by using the CosmoMC sampling software.

Skills required:

Good python programming skills are required for the ingestion, manipulation and visualisation of point source catalogue information.

Confidence to modify, recompile and run C/Fortran code is a necessity for computing the effects of varying point source masks on the power spectra of cosmic microwave background data.

An ability to compile and run the CosmoMC sampling software would be required to investigate effects of mask changes on cosmological parameters.

Strong mathematical and statistical skills are required in order to understand the properties of the power spectra of masked maps and the mask-deconvolution procedure (see e.g. Efstathiou 2004, PL15). It is important to have an appreciation of the “LCDM” model of cosmology and of the
Useful references:

The Planck Legacy Archive will be a key resource for the project, see:

https://wiki.cosmos.esa.int/planckpla2015/index.php/Main_Page

At this site there are descriptions and download instructions for the various catalogues and maps required for this project.

The CosmoMC sampling software is available at:

https://cosmologist.info/cosmomc/

General references:

Efstathiou 2004: Myths and Truths Concerning Estimation of Power Spectra,

PCCS15: Planck 2015 results. XXVI. The Second Planck Catalogue of Compact Sources,
https://arxiv.org/abs/1507.02058

PL15: Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters,
https://arxiv.org/abs/1507.02704

20. 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:**
Cosmological simulations from the Sherwood simulations suite will provide the necessary physical properties to calculate realistic mock He II absorption spectra. An excursion set code will thereby be used to model the progression of the overlap of He II regions for a range of assumptions for the evolution of the QSO luminosity function. The evolution of the He II 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 He III regions,
- post-processing of the hydro-dynamical simulations with the adapted excursion set code.
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 He II Lyman-alpha absorption as a function of redshift from Puchwein et al. (2015).

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.
### 21. Can Gaia data solve the mystery of the stellar breathing pulses?

| Supervisor I: Ghina Halabi, Hoyle Building H32, email: gmh@ast.cam.ac.uk |
| Supervisor II: Carlos Gonzalez-Frenandez, APM A05, email: cgonzal@ast.cam.ac.uk |
| UTO: Christopher Tout cat@ast.cam.ac.uk |

#### Project summary:

Core helium burning in stars is, in some cases, convectively unstable. It is not clear whether this instability is a computational artefact or it actually happen in stars. This project aims to use high-precision Gaia observations to constrain the stellar models and gain insight on whether this instability is a physical phenomenon or not.

#### Project description:

Stellar evolution (theory) and computational astrophysics (using stellar evolution code and analysing observational data sets).

#### Background:

Stars burning helium in their core are called Horizontal Branch stars. They develop a convective core that becomes enriched in carbon and oxygen. Towards the end of helium burning, a complex situation arises which causes a convective instability, called breathing pulses (Castellani et al. 1985). Theoretically, it is still unclear what causes this instability. Some argue that the helium burning causes the rate of energy production to be enhanced and thus the luminosity increases. The radiative temperature gradient, which is that required for radiative diffusion to be an efficient means of energy transport, is proportional to the luminosity. Thus it increases at the boundary between the convective core and the radiative envelope driving this region to become convective. This means that abrupt mixing occurs between the almost totally He-depleted carbon-oxygen core and the overlying helium-rich layers bringing in fresh helium to the core (i.e. a breathing pulse), prolonging the helium-burning lifetime. Another scenario that has been proposed is that the central temperature and density conditions make free-free transitions the dominant source of opacity. Therefore the increasing carbon and oxygen abundances cause the opacity to increase, consequently increasing the radiative temperature gradient and the region becomes convective.

#### Project details:

The occurrence of these breathing pulses in stellar models thus depends on the criterion used for convection (Constantino et al. 2015). It is still unclear whether it is an artefact of the way convection is modelled or whether it does actually happen in stars. The proposed project aims to explore exactly this. One way to constrain the models and draw substantial conclusions is to resort to high-precision photometric observations. Gaia DR2 provides very detailed Hertzsprung-Russell diagrams (HRDs) so the data have sufficiently accurate positions to differentiate between Horizontal Branch stars (otherwise known as red clump stars) and red giants. Quantifying the number of stars in each group will give insight on the helium burning lifetimes. This can then be compared to a simulated population of stars. If the simulated population is predicted to have fewer red clump stars than observations, we know that the models
underestimate the helium burning lifetime and thus breathing pulses do happen. Otherwise, we know that this is only a numerical artefact.

The first step the student will need to do is to investigate whether there is any physical mechanism that can explain the occurrence of breathing pulses. This can be done using the Cambridge Stellar Evolution code stars. Then the student will run the Cambridge population synthesis code to generate a simulated set of stellar models from the Zero-Age Main Sequence till the Asymptotic Giant Branch phase. The third step will be to query data from the Gaia database and generate high-quality HRDs. Conclusions can be drawn by comparing the observed sample to the simulated set of models. The project thus entails sufficient understanding of the underlying physics and provides excellent opportunity for the student to learn about stellar evolution as well as observational data from Gaia.

**Nature of the Project Work:** Computational.
* Learn how to use the Cambridge stars stellar evolution code and population synthesis code.
* Understand and model the evolution of stars from the ZAMS to the AGB phase.
* Generate a set of simulated models which can be compared to observationally inferred temperatures and luminosities.

**Skills required:**
Knowledge of stellar evolution is essential. The part-II course on Structure and Evolution of Stars suffices but the part-III course is desirable.

**Useful references:**

General references:
22. Host galaxy properties derived from a statistical analysis of quasar spectra and photometry

Supervisor I and UTO: Paul Hewett (Office: H19 E-mail: phewett@ast.cam.ac.uk)
Supervisor II: Manda Banerji (Office: K19 E-mail: mbanerji@ast.cam.ac.uk)

Project summary: Luminous quasars outshine the light from their host galaxies by a very large factor. In the ultraviolet through near-infrared portion of the spectrum, however, a host galaxy can produce a number of specific signatures, including i) emission from gas ionised by high-mass stars, ii) the absorption and scattering of light from the quasar by gas and dust in the interstellar medium of the host galaxy and iii) the contribution of starlight to the spectral energy distribution (SED) of the quasar. The project will focus on undertaking a comprehensive assessment of the weak host galaxy signatures in a large sample of luminous quasars with a view to obtaining a better understanding of how quasar and host galaxy properties are related.

Project description: 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 (MgII\(\lambda\lambda 2796,2803\)) in gas associated with host galaxies, or outflowing material from the quasar, are available for the DR7 and DR14 quasars. Photometry in the SDSS optical (ugriz), near-infrared (JHK) from the UKIDSS and VHS surveys and mid-infrared (W1W2) passbands is also available for many of the quasars. For objects with redshifts 0.4<z<2.0 the observed-frame wavelength coverage ~3000-45000Å of the photometry allows SEDs to be studied over rest-frame wavelengths ~1600-20000Å.

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. Rather little work, however, has been undertaken in trying to identify the presence of starlight from such host galaxies. 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.

Background: A significant fraction of 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.

Project details: The quality of the SDSS quasar spectra is good and the wavelength range probed by the photometric data is well-suited to separating contributions from quasar and galaxy. One cannot though escape from the fact that, in any individual spectrum, the galaxy signature is weak and hard to detect. Progress can only be expected via the careful combination of sub-samples of quasar spectra and photometry to enable the detection of small systematic differences in the quasar SEDs due to the presence of host galaxies [with different properties].
Skills Required: 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.

The student will need to be comfortable with such a “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 is important. 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:

The SDSS DR7 and DR14 web pages: http://www.sdss.org/dr7/ and http://www.sdss.org/dr14/
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.
23. Unlocking the Transient Sky

Supervisor I: Simon Hodgkin (H39, sth@ast.cam.ac.uk)
Supervisor II: Sergey Koposov (Affiliated Lecturer, skoposov@cmu.edu)
UTO: Vasily Belokurov

Project summary:

The aim of this project is a broad clustering and classification exercise of the million transients per day coming out of the Zwicky Transient Facility (ZTF). This is an unprecedented scale for a transient survey and is a pre-cursor to the Large Synoptic Survey Telescope (LSST), which will observe the whole sky every few days down to unprecedented depths.

Project description:

The student will explore data from ZTF to build a better understanding of the transient sky as a function of various parameters (magnitude, colour, amplitude, timescale: see Fig 1). ZTF began operating in June 2018, and surveys the sky with a wide field camera on the 1.2-m telescope located at the Palomar Observatory (California). Each night ZTF generates about a million alerts. However at the moment only tiny subsamples of the brightest examples are analysed. Machine learning approaches will be exploited to classify transients and identify the rarest and most unusual events (for example kilonovae associated with gravitational-wave events, Smartt et al. 2018).

Figure 5: From Rau et al. 2009 Showing peak R-band magnitude (brightness) versus decay time for a range of transient classes. There is plenty of empty parameter space, and poorly defined classes of never observed objects in the figure. See the paper for a full explanation.

Background:

Astrophysics is currently experiencing a major transition. While 15-20 years ago the sizes of the datasets available to us was only in the realms of millions of objects, now large survey projects produce catalogues comprising billions of objects. One upcoming (and particularly challenging)
One key product of such a powerful survey will be **millions** of objects uncovered **every day** that are variable or transient, caused by a variety of astrophysical processes such as stellar flares, explosions, accretion of material onto a (supermassive) black holes, gravitational lensing and many others.

At this point in time however we are just not able to deal with such a flux of new exciting objects. In particular, we are not able to understand quickly what each of those objects are, and possibly identify the most exciting ones among thousands of less interesting objects. Dealing with this problem requires involving some machine learning, big data tools as well as using every auxiliary dataset available to us (such as X-ray, Radio, UV, IR etc) as that should allows us to better understand each event.

While the data from LSST is not due to start arriving for another couple of years, there is a project that provides a flow of data comparable to what will be expected from LSST. This project is the ZTF -- Zwicky Transient Factory.

**Project details:**

We propose that the student analyse this exciting unexplored dataset in order to be able to understand which classes of objects are appearing in the transient sky, and what are their properties. To do that would require analysing the catalogue of events and combining it with large catalogues of auxiliary datasets available in Cambridge. This would create a highly dimensional sparse dataset which we would then investigate using various machine-learning techniques, such as deep learning, Gaussian mixture models, random forests, and clustering methods. This should allow us to understand broad classes of objects seen in the data, such as the active nuclei of galaxies, supernovae, novae, cataclysmic variables, planetary transits, but also will allows us to find new yet unexplored classes of objects.

**Skills required:**

Familiarity with or strong desire to learn how to handle large astronomical datasets would be of benefit, as well as some programming experience. Knowledge of Python and databases (using e.g. SQL) would also be helpful.

**Useful references:**

- *A kilonova as the electromagnetic counterpart to a gravitational-wave source*, Smartt et al. 2018, [http://adsabs.harvard.edu/abs/2017Natur.551...75S](http://adsabs.harvard.edu/abs/2017Natur.551...75S)


Automating Discovery and Classification of Transients and Variable Stars in the Synoptic Survey Era, Bloom et al. 2011: http://adsabs.harvard.edu/abs/2012PASP..124.1175B

https://ztf.uw.edu/alerts/public/ – The public archive of all ZTF archives
24. A new window on the composition of planets and disks

Supervisor I: Mihkel Kama (H36, mkama@ast.cam.ac.uk)
Supervisor II: Colin P. Folsom
UTO: Cathie Clarke

Project summary:

Accretion from a disk or evaporating planet can leave a measurable “contamination” fingerprint on the stellar photosphere of a star. This has recently yielded new insights into the material content and composition of terrestrial planet forming regions of disks, which are otherwise hard to probe. To expand on this work, we obtained spectra of a number of stars hosting protoplanetary and debris disks of interest. In this project, you will determine stellar abundances from these spectra and perform entirely new analyses of planet-forming disk elemental composition.

Project description:

The main aims are to obtain elemental abundances for the observed sample of stars and to perform analyses relating the inferred composition of the accreting material to the structure, age, and other properties of the circumstellar disk of material.

The technique in question works for stars with radiative — thus slowly-mixing — envelopes (Jermyn & Kama 2018). Even modest accretion rates can lead to a photospheric composition representative of the infalling material, rather than the bulk of the star. This is a novel approach to studying circumstellar material, and the IoA is pioneering the field. You will be taught to use standard tools of the stellar spectroscopy field to determine stellar atmospheric parameters and the abundances of two dozen elements, including those of interest for volatile delivery to terrestrial and giant planets, but also many elements which are dominant components in asteroids and planetary cores. There is space to expand this work to improve the existing tools, in particular by applying Markov Chain Monte Carlo techniques to understand correlations in the posterior parameter values.

Interpretation of the data will include reviewing the structure (radial dust surface density distribution) and other observable properties of the systems, as well as model predictions for gas accretion rates in the debris disk systems; and looking for corresponding variations in abundances in the stellar surface.
Background:
Statistics on exoplanet occurrence rates, sizes, and orbital locations are steadily improving. Protoplanetary and debris disk studies in continuum and CO emission are also advancing rapidly. To understand the connections between planet formation processes and outcomes in terms of planet cores and atmospheres, and test proposed models, we need to observationally characterise elemental compositions. Yet information on the elemental composition and gas/ice/rock partitioning of even the most common volatile elements (C, O) is hard to get. Our stellar contamination analysis technique is a new window onto a rich world of gas and solid-state abundances in circumstellar material.

Skills required:
Ability, or willingness to learn, to write basic input/output, analysis, and plotting scripts in Python will be useful. Ability to read Fortran and C code will be beneficial, but not essential. Depending on your skills and preferences, we can vary the coding component of the project.
25. A Song of Ice and Fire: sulphur in protoplanetary disks

| Supervisor I: Mihkel Kama (H36, mkama@ast.cam.ac.uk) |
| Supervisor II: Oliver Shorttle |
| UTO: Cathie Clarke |

**Project summary:**
Sulphur is one of the most abundant elements in the Universe. It is a major player in astro-, geo-, and biochemistry. Current planet formation models cannot include sulphur in its refractory (rocks) and volatile (gas and ice) forms, because we do not understand how sulphur is processed between the gaseous and solid phases. Motivated by new measurements of sulphur in protoplanetary disks by our team, this project centers on developing a 1D physical-chemical model for parameter studies of how sulphur entering a disk in gas- or ice-phase molecules like H$_2$S is converted into rocks. Under what conditions can we reproduce measurement results for meteoritic rocks and cometary rocks and ices? Are there stars around which this processing is much more, or much less, efficient than around the young sun? What are the implications for observing sulphur-bearing molecules and hazes in exoplanets?

**Project description:**
You will build a model to explore how the outcomes of parametric equations describing volatile-to-refractory sulphur processing (a prominent example: from H$_2$S gas into FeS rocks) vary within a protoplanetary disk, and as a function of time, assumptions on the nature of the material feeding the disk, and other aspects of the early evolution of planet-forming material. The model will be constrained by the latest results quantifying the total abundance of rocky sulphur carriers in disks, and by planetary and planetesimal abundances from solar and extrasolar systems. The preferred programming language will be Python, and through the project you will become familiar with the overall theory of planet formation and disk evolution, as well as the essentials of astrochemistry.
Background:
Most work connecting planets to their formation in disks centers on carbon and oxygen. We are expanding that frontier to include other abundant and important elements. The nature and relative importance of rocky, icy, and gaseous sulphur carriers in star- and planet-forming environments (protostellar cores and protoplanetary disks), for example, is not yet well understood. Our team is doing some of the leading work on this topic, and your project will allow to translate our latest results into a wider context, making predictions for observations of disks around stars of different age and mass, as well as for planetesimal and planet cores and atmospheres around the older counterparts of these systems. With the ever-impending launch of the James Webb Space Telescope, the study of sulphur-bearing molecules and hazes in exoplanets will gain a firmer observational footing, and your work will allow us to be prepared for this era.

Project details:
You should be willing to learn, or already be able to translate a conceptual/mathematical physical model into a computer program to solve the relevant equations and provide output in text and graphics. The preferred language is Python. A general background in physics will be essential and a cursory familiarity chemistry terminology will be beneficial, but by no means essential. A curiosity to explore the meaning of your results, play with input parameters, and willingness to explore the related literature will also be advantageous.

Useful references:
Lauretta et al. (1996) studied the H2S -> FeS reaction and placed it in the context of the young solar system (the “solar nebula” protoplanetary disk). This is one of the processes you will be considering in a 1D disk model, mapping the evolution along the entire disk and explore the variation resulting from different input assumptions, which has never been done for sulphur.
26. Giant planets and the composition of planet-forming disks

Supervisor I: Mihkel Kama (H36, mkama@ast.cam.ac.uk)

Supervisor II:

UTO: Oliver Shorttle

Project summary:

The inventory of biologically relevant volatiles (e.g. water, carbon) in planetary bodies determines their physical and chemical evolution and ultimately their habitability. Critical volatile elements in this respect are C and O, the abundances of which are set during planetesimal formation. Their volatile content is influenced by their internal thermal and compositional processing and also by disk structure. This project focusses on the latter influence, as recent observational and theoretical results, focussed both on our own solar system and on other stars, show the profound impact giant planets can have on disk structure. The implications of this for the volatile element budget of planetesimals has yet to be fully explored, and it is this that you will address.

Project description:

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. For example, Earth and all inner solar system solids are remarkably poor in carbon; some asteroids are water-rich while others are dry. Thousands of exoplanets are now also known and attention is increasingly shifting to more detailed characterisation of their properties. It is, therefore, increasingly important to understand what sets the elemental composition of the building blocks of planets.
Project details:

The student will work with an existing 3D physical-chemical model for disk structure and chemistry and use this to probe how giant planet formation affects the distribution of disk volatile species (e.g. H2O, CO). The student also has the opportunity to develop their own 2D disk model based on an existing code skeleton developed at IoA, to explore how additional physical processes could impact the results derived from the more complex model. The main area of interest is to explore scenarios under which giant planet formation may perturb the composition of volatile reservoirs in the disk. Observational comparisons can be carried out with the composition of protoplanetary disks and exoplanet atmospheres.

Skills required:

You will be running a Fortran code. Knowledge of this language will not be needed, but may be useful and can be acquired as necessary during the project. It will be useful to know or be willing to learn some Python, in particular to read datafiles from the modelling code and make plots as needed. 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.

Useful references:

Min et al. (2009)
Öberg et al. (2011)

General references:

Review on protoplanetary disks, Williams & Cieza (2010)
27. The search for hidden supermassive black hole growth in quasars

Supervisors: George Lansbury (H51, gbl23@ast.cam.ac.uk)
Dominic Walton (dwalton@ast.cam.ac.uk)
UTO: Andy Fabian (acf@ast.cam.ac.uk)

Background: Supermassive black holes (SMBHs) at the centres of galaxies grow by accretion of matter from their surroundings, with the most rapidly growing objects shining brightly as quasars, the most luminous persistent astrophysical objects in the Universe (e.g., Soltan 1982). According to models, at least half of the cosmic growth of SMBHs occurs during highly obscured quasar phases (e.g., Fabian 1999; Gilli et al. 2007), where the central black hole is hidden beneath dense layers of surrounding gas and dust. Observationally identifying the most deeply hidden quasars is challenging, however, due to their inherent faintness across the electromagnetic spectrum. As a result, few of these systems are robustly identified (e.g., Lansbury et al. 2015), and important questions remain unsatisfactorily answered from an observational perspective. What fraction of cosmic black hole growth occurs in highly obscured quasar phases? Do highly obscured quasars represent an important evolutionary phase, or is obscuration simply a result of the observer’s viewing angle (e.g., Ricci et al. 2017)?

This project: The main aim of this project is to identify new highly obscured quasar candidates, and significantly increase the census of this elusive population of growing SMBHs. The starting point for the search will be quasars identified in the recent phase of the Sloan Digital Sky Survey (SDSS-III; Alam et al. 2015), a revolutionary optical spectroscopic survey of the northern sky. These will be cross-matched with the large data sets available from the X-ray space satellites Chandra, XMM-Newton, Swift, and NuSTAR. Since X-rays are emitted from the immediate vicinity of the black hole, and penetrate through obscuring material on the path to the observer, the X-ray data allow us to quantify gas absorption (i.e., obscuration) and identify deeply hidden systems. The project has discovery potential, and the highly motivated Part III student will perform a detailed physical characterisation (e.g., spectral modelling) of the most interesting systems identified.

Left: Optical image of a galaxy known to host a highly obscured quasar. Right: Artist impression of an obscured quasar (Image: nasa.gov/feature/nustar-斯塔雷斯深进入隐藏的黑洞).
Nature of the project work

The project is both observational and computational in nature, and will involve utilising large observational data sets from a range of sources. Basic programming skills are required.

Useful references

Zakamska et al. 2003, AJ, Candidate Type II Quasars from the Sloan Digital Sky Survey
Lansbury et al. 2015, ApJ, NuSTAR Reveals Extreme Absorption in z<0.5 Type 2 Quasars
28. High-temperature Chemistry in Exoplanetary Atmospheres

Supervisor I: Nikku Madhusudhan, H18, Email: nmadhu@ast.cam.ac.uk
Supervisor II:
UTO: Nikku Madhusudhan

Project summary:
The project will investigate the chemical compositions of exoplanetary atmospheres that are possible under extreme conditions and that are observable with current and upcoming observational facilities. The particular focus of this project will be high-temperature metal-rich gases that are not observable in atmospheres of giant planets in the solar system but may be observable in exoplanetary atmospheres.

Project description:
This is a computational project and will be conducted in two steps as follows.
1. We will use thermochemical calculations over a range of exoplanetary atmospheric parameters (e.g. temperature, metallicities, elemental ratios, etc) to investigate prominent metal-rich species that are feasible in gas phase under such conditions in chemical equilibrium.
2. We will investigate which of these species from step 1 above can exist in the observable upper regions of an exoplanetary atmosphere considering that some of them may condense and settle down to deeper regions depending on the temperature profile of the atmosphere.

Background:
Characterizing the atmospheres of exoplanets is a major frontier in exoplanetary science. There has been tremendous progress in detecting chemical signatures in exoplanetary atmospheres through their spectra. In particular, the majority of such detections have been made for hot (> 1000 K) giant planet atmospheres. Several commonly known gases, such as water vapor, are in gas phase at those temperatures and are hence readily detectable in spectra given the right instruments (Madhusudhan et al. 2016). While relatively volatile gases (e.g. H2O, CO, CH4, etc) are readily detectable it is unclear how abundant are more metal-rich refractory species in such atmospheres. It has been argued that, given the high-temperatures, metal-rich species such as silicates, TiO, VO, Fe-based species, etc., could be present and observable in such atmospheres (Visscher et al. 2010, Wakeford et al. 2017, Pinhas & Madhusudhan 2017). The goal of the present project is to conduct a systematic study of refractory species that are feasible and observable in exoplanetary atmospheres.

Project details:
The two parts of the project will be pursued as follows.
1. The calculations of chemical compositions, under the assumption of chemical equilibrium, in different conditions will be carried out using computational codes that are available in the group. In the current project, we will be particularly interested in gas phase refractory chemistry, i.e. of those species that have very high melting/sublimation temperatures which also tend to be species that are metal-rich such as silicates (e.g. Visscher et al. 2010).
2. For step 2, we will consider (a) model temperature profiles of exoplanetary atmospheres under different conditions, (b) condensation curves of the various chemical species, and (c) the possibility of vertical mixing of the species, to investigate the survivability of species in observable atmospheres. This will involve numerical modeling of the condensation and mixing processes (e.g. Spiegel et al. 2009).

Skills required:
Part-I level physics and chemistry will be sufficient for the project. The project will require adequate
computing skills including familiarity with data handling and some numerical modeling experience.

**Useful references:**

**General references:**
Madhusudhan et al. 2016, Space Science Reviews, 205, 285
**29. 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 simulated and observed high redshift (z>6) quasars in the epoch of reionization in order to investigate if and how different near zone size estimators can be used to constrain the neutral hydrogen fraction; clumpiness of the Universe and the ages of quasars in the epoch of reionization.

**Project description:** Measurements will be made by modifying existing software to analyze simulated data using the results of numerical simulations from Keating et al, 2015 by combining simulated absorption spectra generated from these numerical simulations of the intergalactic medium with simulated rest frame ultra-violet quasar spectra. You will compare measurements from these simulations with measurements from our recent observational data. The simulated data will be analysed over a range of spectral resolutions with the addition of experimental statistical noise in order to match the existing observations and also over a range of resolution spectral (100-1000 km/sec) and signal to noise ratios in order to guide the design of future observations. 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.

**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 the ionized near zones around high redshift quasars. These recent observations (Figure 10 from Reed et al, 2017) support a picture where there is 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 over the whole redshift range all redshifts 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. The project will also introduce you to extragalactic observational astronomy and data analysis.

**Skills required:**

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

**Courses needed are:**
- Formation and Structure in the Universe

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

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

![Figure 1: Optical spectrum of a high redshift quasar showing redshifted hydrogen Lyman-α ($\lambda_{\text{rest}}=121.6\text{nm}$) emission and absorption signatures including near-zone region. Note the observed wavelengths of these UV transitions are observed in the red part of optical window. The goal of the project is to measure in a robust and repeatable manner the sizes of the near-zones in observations and to compare with the result with similar measurements on existing numerical simulations.](image)
Project Summary:

The project aims to study potential sources of confusion in our attempt to measure deviations from Gaussianity in the Cosmic Microwave Background (CMB). Specifically, next generation CMB experiments could be sensitive to signatures sourced by the presence of new particles in the very early Universe. However these experiments, which aim to observe the CMB with unprecedented precision, will also pick up contributions from late time, extra-galactic physics (secondaries) and galactic foregrounds. This project will focus on identifying, calculating and simulating the non-primordial sources so that a unbiased measurement of the primordial component can be obtained.

Background:

Next generation ground based Cosmic Microwave Background (CMB) experiments, such as the Simons Observatory, aim to detect relics of primordial gravitational waves. The B-mode polarisation pattern of the CMB is uniquely sensitive to primordial gravitational waves. Sometimes referred to as the holy grail of cosmology, the first challenge is to measure the power spectrum, the Fourier equivalent of the 2-point correlation function of fluctuations (variance in 1d). If the gravitational waves in the early Universe were sourced by simple, linear physics, their statistical distribution will be completely determined by the power spectrum. However, theoretically it is very plausible that the physics is more involved, which could easily introduce deviations from Gaussianity. These signatures of non-Gaussianities, which can be most easily constrained using the bispectrum (the Fourier equivalent of the three point function or skewness in 1d), have been carefully looked for in the Planck and WMAP maps. These maps however had very limited polarisation sensitivity. Furthermore, the non-Gaussianities that were the main focus of these searches did not include possible signatures of gravitational waves.

Recent theoretical developments have shown that unique signatures are predicted when the Universe contains (a hierarchy of) new particles, with different masses and spins (). These particles can interact and these dynamics can be imprinted on the initial conditions that source the small density fluctuations in the early Universe. If gravitational waves are involved in these interactions then we would expect to find correlations between the polarisation and temperature maps. The precise correlations should be indicative of the mass and spin of these new particles, and for this reason, this branch of cosmology has been referred to a cosmological collider experiment.

Unfortunately, the signatures, even in optimistic scenarios, are expected to be small. For that reason it is extremely important to understand possible sources of confusion. For example, polarisation and temperature maps will be correlated, even in the absence of primordial non-Gaussianities, because late time physics can introduce effects that trace the potential in different ways. A well-known example is the so-called ISW-lensing bispectrum, which correlates the late time Integrated Sachs Wolfe effect (ISW) with the lensing potential. Recently, it was shown that there other sources of contamination from ISW correlated with the Sunyaev Zeldovich effect. Unfortunately these effects are a little harder to quantify and they rely, to some degree, on astrophysics. There are also (galactic) foregrounds and points sources which can induce non-zero higher order
correlations. These sources need to be quantified as they will likely dominate the primordial B-mode signal, for example the primordial signal is already known to be subdominant to galactic polarised dust.

Although substantial work has been done to qualify a large number of these effects, the main focus of these studies was to obtain estimates for non-Gaussianities that could confuse bispectra sourced by scalars. Since scalars are not directly traced by B-mode polarisation, none of these studies explored the effect on a search for non-Gaussianities sourced (in part) by gravitational waves. Since we expect a significant improvement in the measurement of the B-mode pattern in the CMB with upcoming experiments, and we hope to find deviations from non-Gaussianities, it is timely to start identifying all sources that could possibly confuse a signal of primordial gravitational waves.

**Project details:**
First, all possible secondary sources of contamination that involve B-modes should be identified. Several studies will prove helpful in the identification, namely Lewis, Challinor and Hanson (2011), Pratten and Lewis (2016), Coulton et al (2017) and Hill (2018). Specifically, in Pratten and Lewis it was claimed CMBS4 may be sensitive to curl lensing from post-Born effects in the bispectrum. Such a bispectrum could possibly obscure primordial non-Gaussianities. The effects should be calculated for the correlations of relevance when constraining the primordial bispectrum. Second, galactic foregrounds are large and their effect on estimates of primordial non-Gaussianities is hard to quantify analytically. For that reason, estimators that have been developed by the supervisors (Duivenvoorden et al in prep, Coulton et al in prep) to extract primordial non-Gaussianities from CMB data should be tested on simulations that contain galactic foregrounds. Simulations can be generated using existing software packages such as PySm, or use full sky simulations publicly available (Vansyngel et al (2016)). Results should be analysed and should lead to a broad classification of sources of contamination as well as a strategy to mitigate these effects (for example by considering only specific bispectra in the case of secondaries or using multi-frequency techniques in the case of foregrounds).

**Skills required:**
The project is discovery based and well suited to a student interested in gaining experience in analytical computations as well as numerical codes. Relevant lecture courses: Introduction to Cosmology, Formation of Structure in the Universe. The student will be expected to write code in Python, Fortran or C++ and to learn some existing codes.

**Refs:**
Lewis, A., Challinor, A., & Hanson, D. 2011, JCAP, 3, 018
Pratten and Lewis, JCAP 1608, 047 (2016), arXiv:1605.05662

For some introduction on the topic:
Popular article on the science:
31. A lab prototype of a self-aligning space telescope (SUPERSHARP)

**Project summary:**

The student will write software to move individual primary mirror segments so that they act as a single mirror surface. This requires positioning the mirrors with an accuracy of ~50nm. The lab prototype has 3 mirror segments each of which has computer-controlled nano-positioners providing tip, tilt and piston of the mirror surface. The prototype also has a metrology system at the centre of curvature of the mirrors, which provides measurement of the mirror positions with a precision of ~30nm. The software will capture raw data from the metrology system, analyse this data to determine the position errors of the mirror surfaces and then move the mirrors to remove these position errors. This process will be repeated continuously with a cadence of less than 1 minute to maintain accurate mirror alignment.

**Project description:**

The project milestones are:

1. Close the loop using the finite conjugates at the centre of curvature of the mirrors. Initially the mirrors have to be co-aligned and co-focussed (error ~20μm) from a random starting position with very large position errors (up to a few mm). They then have to be co-phased so that the position errors are ~50nm and continuously adjusted to maintain this alignment.
2. Demonstrate good imaging at the prime focus for a target at an infinite conjugate. In the lab, this will be done by using a large flat mirror to operate the telescope in double-pass.
3. Demonstrate good imaging at the prime focus using a real stellar image. To do this, the prototype will be piggy-backed on to one of the IoA’s telescopes.

**Background:**

Although there are some examples of telescopes that employ regular alignment procedures to maintain good image quality (JWST, VISTA, HET, SALT, E-ELT, etc.) no existing or planned telescope uses an internal light source to close the control-loop on a fast timescale while simultaneously observing science targets. This is the essence of the SUPERSHARP (Self-aligning Unfolding Primary for Exo-planet Research via Spectroscopic High-Angular Resolution Photography) telescope concept. This approach has several advantages for space telescopes.

- The telescope can be folded up so a large telescope can be much smaller in its launch configuration.
- The telescope structure can be very light-weight and it does not need to be thermally stable on long time scales.
- The ground-based testing program is identical to the way it will operate in space, which significantly reduces risk.

Angular resolution (the ability of a telescope to see fine detail) depends on the size of the primary mirror (angular resolution in radians ~λ/D where λ is the wavelength of the light and D is the longest baseline across the primary mirror). The largest rocket fairings are about 4.5m in diameter.
so telescopes bigger than 4.5m diameter require an unfolding design. SUPERSHARP offers telescopes, which become ~5-10x bigger in their unfolded configuration.

This has enormous potential for all aspects of astronomy. In particular, it offers a way to search for bio-signatures in a large sample of Earth-like exoplanets (see arXiv:1507.04779 and arXiv:1801.06111) - a project which requires a space telescope with D>8m.

Project details:

Zemax model of the 3 mirror prototype showing rays to and from the metrology system at the centre of curvature. The individual mirrors are 75mm in diameter.

Left: Point spread function (PSF) of a single mirror. Right: PSF of all 3 mirrors when perfectly aligned. Both images are on the same scale.

Schematic layout of the prototype.

Two views of the CAD model of the mirrors and their actuators.

Pictures of the lab prototype.

Skills required:
Software will be written in Python. Experience with control hardware such as Arduino and Raspberry Pi would be useful.

Useful references:


arXiv:1801.06111 “SUPERSHARP – Segmented Unfolding Primary for Exoplanet Research via Spectroscopic High Angular Resolution Photography”, Ian Parry et al, 2018
Unlocking the mysteries of optical/UV variability in quasars

Supervisor I: Professor Chris Reynolds (room H15, csr12@ast.cam.ac.uk)
Supervisor II: Dr. William Alston (room H56; wna@ast.cam.ac.uk)
UTO: Prof. Chris Reynolds

Project summary:
In this project, you will analyse recent state-of-the-art computer simulations of black hole accretion disks in a quest to understand the optical/UV emission of quasars and luminous active galactic nuclei (AGN). Powerful and variable optical/UV emission has been a defining characteristic of AGN ever since their discovery 50 years ago. This emission is attributed to the thermal radiation from the accretion disk around the supermassive black hole. However, this standard model seems to fail in several important regards; the observed variability is much more rapid than naively predicted, and there are time-lags between variations at different optical/UV wavelengths that are still not fully understood. Here, you will conduct new analyses of our recent disk simulations, comparing predicted optical/UV variability with observations from the literature. Ultimately, this will allow us to connect the observed characteristics of AGN to the detailed physics of accretion disks (especially magnetohydrodynamic turbulence and dynamo action).

Project description:

Density rendering of accretion disk simulation from Hogg & Reynolds (2018a)

As part of a recent PhD project (Hogg & Reynolds, 2016, 2018a, 2018b), we have constructed and run a set of new accretion disk simulations; these are high-resolution simulations (thereby capturing the turbulent dynamics adequately), and followed the accretion disk evolution for a large number of inner-disk orbital periods (thereby allowing us to analyse the time-variability characteristics in detail). For such computations to be tractable, however, required that we included rather simple physics – while the MHD was treated in full, radiation physics was implemented in a rudimentary manner. Even then, the longest of these simulations took several million CPU-hours to compute!

In this project, you will examine AGN optical/UV spectrum and time-variability by “painting” the relevant radiation processes onto these accretion disk simulations. To start with, we will examine simple models where each patch of the disk is assumed to radiate as a blackbody, with the luminosity/temperature set by the instantaneous turbulent dissipation in the disk body below that patch. The resulting characteristics of the optical/UV variability (power spectra, coherence, and
time-lags) will then be calculated and compared with observations from the literature. We will then build up complexity from there, including non-blackbody terms and reprocessing of the X-ray emission from the central disk by the outer optical/UV disk. This will constitute one of the most detailed theoretical studies of optical/UV variability from AGN to date and is a crucial step in assessing whether we need to fundamentally re-think the standard picture.

Skills required:
Prior experience with either python or IDL is essential. Must be comfortable with Fourier transforms, and general comfort with UNIX/LINUX environment is desirable. Completion of Part II Astrophysical Fluids (or equivalent) also highly desirable.

Useful references:
General references:
Lawrence, A., 2018, Nature Astronomy, vol 2, pp.102
33. Chemical signature of a dwarf galaxy merger onto the Milky Way

Supervisors: Jason Sanders, H33, email: jls@ast.cam.ac.uk
UTO: N. Wyn Evans, H50, email: nwe@ast.cam.ac.uk
UTO: Vasily Belokurov, H20, email: vasily@ast.cam.ac.uk

Project summary The stellar halo consists of an in-situ component and an accreted component that form distinct chemical abundance sequences. The aim of this project is to construct chemical evolution models of these sequences assuming the accreted component came from a single dwarf galaxy merger.

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) but the relative importance of these two processes is not well known. However, the halo stars retain memory of their origin through both their patterns of chemical elements and their kinematics. The chemical evolution of galaxies predicts stars lie along a sequence in \([\alpha/Fe]\) and \([Fe/H]\) [e.g. 6]. Two of the 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 \(\sim 1\) Gyr) Type Ia supernovae begin contributing producing more iron than \(\alpha\) elements and giving rise to 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 halo [5, 3] 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. The astrometric data from Gaia has provided accurate kinematics for many halo stars and globular clusters within the Galaxy. This data indicates that the kinematics of the halo and of the globular cluster population of the Milky Way experienced (at least one) large dwarf galaxy merger onto the Milky Way \(\sim 10\) Gyr ago [1, 4].

Project description and details The student will investigate modelling the chemical abundance patterns in the stellar halo using a two-component chemical evolution model – one component will consist of early star formation within the Milky Way disc and one component for the dwarf galaxy. The student will primarily investigate reproducing the sequences in \([\alpha/Fe]\) and \([Fe/H]\) observed in APOGEE data [c.f. 2] as well as similar data from the LAMOST survey, but this can be extended to include other chemical abundances measured by APOGEE or the GALAH survey. It should be possible to constrain the star formation rate within the accreted dwarf galaxy as well as possibly the time of merger onto the Milky Way.
**Skills required** The student should be familiar with both C++ and Python.

### Project summary:
The systematic study of supermassive black hole orbits in simulated galaxies to pin down the regime in which dynamical friction is acting properly and to devise new prescriptions that take into account dynamical friction effects on the unresolved scales.

### Project description:
Accurate motions of supermassive black holes (SMBHs) in supercomputer simulations of galaxy formation are needed not only to follow their dynamics meaningfully, but also to be able to couple energy released by accreting black holes in correct spatial locations. Moreover, with the advent of gravitational wave astronomy it is of paramount importance to pin down the cosmic merger rates of supermassive black holes whose predictions rely crucially on accurate black hole orbits. Current state-of-the-art simulations (e.g. Vogelsberger et al. 2014, Weinberger et al. 2017) adopt very crude prescriptions that take into account dynamical friction on unresolved scales leading to a poor tracking of black hole orbits. This project attempts to improve upon this by performing a series of idealized galaxy simulations where black hole orbits will be studied as a function of resolution and where different models for unresolved dynamical friction (Wurster & Thacker 2013, Hirschmann et al. 2014, Petts et al. 2016, Tremmel et al. 2015, 2017) will be explored and compared against analytical predictions (e.g. Chandrasekhar 1943, Binney & Tremaine 2008).

### Background:
There is firm observational evidence that SMBHs, with masses in excess of $10^{6}M_{\odot}$, reside in the centres of a large fraction of galaxies, including our own galaxy the Milky Way (for a recent review see Kormendy & Ho, 2013). Gas accretion onto SMBHs has been identified as the most likely mechanism powering active galactic nuclei (Lynden-Bell 1969, Rees 1984) which may affect the entire galaxy in which they reside, through a series of physical mechanisms involving radiation, relativistic jets, and fast, mass-loaded outflows. In fact, currently all galaxy formation models include supermassive black holes and their energetic feedback effects as a key ingredient needed to reproduce the morphological diversity of galaxies. While it is still largely debated how active galactic nuclei affect their host galaxies, it is equally important to establish where the feedback energy is released. This entirely depends on the location of the black hole which needs to be tracked accurately in theoretical models. While in principle this can be achieved self-consistently with an accurate gravity solver, in practice the spatial and mass resolution of galaxy formation simulations is often not sufficient to capture the dynamical friction from dark matter, gas and stars acting on black holes properly, instead giving rise to N-body numerical scattering and physically incorrect black hole motion.

### Project details:
The initial conditions of simulations consisting of a live dark matter halo with an embedded baryonic component made of stars and gas will be provided. An off-centred SMBH will be added to this halo and the aim is to study its motion. The student will be expected to use the massively-parallel moving mesh code AREPO and to perform several simulations on our local HPC facilities using these initial conditions. Basic scripts to read simulation data will be provided but the student will need to modify these for the purpose of the project. The project structure is modular. First, purely collisionless simulations at different resolutions will be performed and results will be compared against analytical predictions. Second, a gaseous component will be added to understand how this collisional component affects black hole decay to the centre.
Third, several models for incorporating unresolved dynamical friction in a semi-analytical fashion will be considered (see e.g. Tremmel et al. 2015, Petts et al. 2016). This will require some coding in AREPO. Fourth, time permitting, simulations with black holes accreting at the Bondi-Hoyle-Lyttleton rate and the subsequent injection of feedback will be considered as well as full cosmological runs.

![Figure 1. Simulated dwarf galaxy with two different prescriptions for unresolved dynamical friction acting on SMBHs. Adapted from Tremmel et al. 2015.](image)

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

**Useful references:**

**General references:**
35. Eccentricity Evolution during Wind Mass Transfer

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

Background

Some X-ray binaries, particularly those with a black-hole component, have eccentric orbits. Mass transfer in these systems is believed to take place by the degenerate component accreting from the stellar wind of its usually cool companion. Other binary systems, such as barium stars, show evidence of earlier accretion but have eccentric orbits hinting that mass transfer was via a wind rather than Roche lobe overflow. The accretion rate is then a function of orbital phase and so the eccentricity is not an adiabatic invariant. Models of this process differ fundamentally in their prediction of the rate of change of eccentricity $e$ in that some allow only $e < 0$ while others predict $e > 0$ for some range of mass ratio. None of the models consider the structure of the wind in detail; all make assumptions about the flow of angular momentum. It is these assumptions that lie at the heart of the disparities.

In order to make progress in the understanding of the process, you will construct analytic models of the binary system in which one component, of mass $M_1$, is losing mass via a steady (in an appropriate frame of reference) wind and the other, of mass $M_2$, is accreting from this wind by a Bondi–Hoyle–Lyttleton mechanism. You will use this to follow carefully the transfer of angular momentum between the wind and the orbital motion and of the stars and so resolve the disparity between models with different assumptions, including those used before and more realistic choices. In the first instance you are invited to consider the case $M_1 \gg M_2$ and a fast wind. To a first approximation the gravitational field of the accreting star may be ignored when computing the wind from the mass-losing star; the accretion of the wind may then be considered separately. As a second approximation you might discuss how the wind is perturbed from its zero-order spherically symmetric state by the accreting star, and how that influences the orbits of the two stars. You might also discuss the case $M_1 \ll M_2$. The project can be extended to more realistic systems away from these limits but then it is likely that numerical solutions to the equations will be necessary.

Related Courses

Some knowledge of orbits and Bondi–Hoyle–Lyttleton accretion is necessary. Required details will be covered in the Binary Stars course but that will be too late for the start of the project. The course will however be useful to put the findings in context.

Nature of the Project Work

Mathematical and mildly computational.

* Understand wind accretion in binary stars.
* Understand binary star orbits with changing mass, energy and angular momentum.
* Develop mathematical models for eccentricity evolution during wind mass transfer given a variety of assumptions.

References

Figure 1: A schematic diagram illustrating Bondi–Hoyle–Lyttleton accretion in a binary system with a fast wind. Mass lost from the red primary is gravitationally focussed by and shocks behind the blue secondary. Material with insufficient energy to escape is accreted by the secondary.
36. Dynamical modelling of dwarf spheroidal galaxies

Supervisor I: Eugene Vasiliev (H53, vasiliev@ast.cam.ac.uk)
Supervisor II: N. Wyn Evans (H50, nwe@ast.cam.ac.uk)
UTO: N. Wyn Evans

Project summary:
Construct dynamical models of one or more dwarf spheroidal galaxies (dSph) and measure the distribution of stars and dark matter. The data consists of existing observational velocity measurements for individual stars, and their density profile. The model is described by a combination of a distribution function (DF) for stars and the total gravitational potential (dominated by dark matter). The fitting procedure is to vary the parameters of the model and obtain the best match to the observed kinematics of stars.

Fig.1: Fornax dSph (left) and the dynamical model from Pascale et al.(2018) (right).

Background:
dSph galaxies are very common in the Universe, and a few of them are among the Milky Way satellites, orbiting at distances between tens and hundreds kiloparsecs (much closer than Andromeda, and comparable to the most distant globular clusters of our Galaxy). They contain millions of stars (as opposed to roughly $10^{11}$ stars in the Milky Way), but are believed to be embedded in much more massive dark haloes, whose density profiles remain very uncertain. In particular, it is not yet established conclusively whether the dark halo profiles have central cusps (as predicted by most models of cosmological structure formation) or cores. Likewise, the prospects of indirect dark matter detection through its self-annihilation, which is sensitive to the density profile, are also uncertain. Therefore, it is of considerable interest to use stellar kinematics to put constraints on the total gravitational potential, which is mostly dominated by the dark matter.

For the most massive and well-studied dSph (e.g., Fornax, Sculptor or Draco), there are thousands of stars with measured line-of-sight velocities available in the literature. A recent (April 2018) data release from the Gaia space mission provides the proper motions (velocities in the image plane) for a similar number of stars. Although the uncertainties of individual measurements are rather large, these data could be used at least to filter out the foreground contamination more efficiently, and possibly to improve constraints on the internal dynamics of these galaxies.

Almost all modelling approaches assume that the stars are in an equilibrium, time-independent configuration, and use the observed ‘snapshot’ of stellar positions and velocities to infer both the gravitational potential in which the stars move, and their distribution function (DF). There are
several broad classes of models (see reviews by Battaglia et al. 2013 or Walker 2012): Jeans models use moments of the DF, Schwarzschild models represent the DF as a collection of individual stellar orbits, and 'genuinely' DF-based models deal with analytic expressions for the DF. The different, sometimes conflicting, conclusions reached by various studies, often relying on the same observational data, are likely attributed to model assumptions (e.g., spherical symmetry or the amount of velocity anisotropy) and details of data handling (e.g., binning or not, treatment of contaminants, etc.). This situation is unsatisfactory, and it is desirable to explore the data, using the most general and flexible (yet still practical) modelling approach, and testing its behaviour in various limiting cases by imposing extra assumptions.

One such possibility is offered by the methods in which the DF is represented as an analytic function of actions with several tunable parameters, and the potential is also represented in a flexible functional form. Recently this approach was applied to the Fornax dSph by Pascale et al. (2018), who used the same computer code (AGAMA, Vasiliev 2018) as planned for the present project, but in a more limited context (e.g., assuming spherical symmetry).

**Project details:**

The general procedure for dynamical modelling is as follows: adopt some plausible values for model parameters (both the DF and the potential), construct the model, compute the likelihood of the observed data given the model, and repeat many times for different model parameters.

To start with, the student will familiarize themself with the DF-based method for dynamical modelling, as implemented (partially) in the AGAMA code. Then one would need to test the approach on mock (simulated) data, for which the true parameters are known, in order to gauge the reliability and accuracy of the modelling procedure, and quantify possible biases arising from adopting certain assumptions inconsistent with the actual data. Finally, one would apply the method to one or more dSph galaxies, outline the range of parameters consistent with the data, explore the implications for the dark matter distribution, and ideally make some testable predictions. Given enough time, one could experiment with the use of multiple, chemically distinct stellar populations to improve the dynamical constraints.

**Skills required:**

Knowledge of classical mechanics (in particular, Hamiltonian mechanics and action/angle variables).

Some background in astrophysics is valuable.

Familiarity with Python and/or C++ is desirable.

**References:**


Ultraluminous X-ray Pulsars and Super-Eddington Accretion

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 four identified to-date, and they are poorly understood. In particular, they appear to exceed the theoretical Eddington limit for neutron stars by factors of 100 or more. The main goal of this project is to develop a new, simple accretion disc model and fit to this to the available X-ray spectra to help test the nature of the accretion flow in these remarkable systems.

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 four 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 ULX (Israel et al. 2017b) and NGC 300 ULX1 (Carpano et al. 2018), but 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.

Understanding the nature of the accretion flow in these remarkable systems is a key step in understanding how they’re able to reach such extreme luminosities. Although other possibilities have been discussed in the literature, the accretion rate is likely to be super-Eddington. While sub-Eddington accretion is expected to occur via a geometrically thin accretion disc, a super-Eddington accretion flow is expected to deviate from this simple picture. The inner regions of the disc become geometrically thick as radiation pressure support dominates over gravity (Shakura & Sunyaev, 1973), before transitioning back to a standard thin disk in the outer regions. However, at the current time there is no X-ray spectral model that allows the user to properly test for this predicted radial stratification of the disc. The primary goal of the project will be to update existing accretion disc models to allow for this possibility, and then apply this new model to the broadband X-ray spectra from the known ULX pulsars, and also then potentially the broader ULX population.
Project details:

The student will first work on updating existing accretion disc models to allow for a radially stratified disc. They will then port this model into XSPEC, an X-ray spectral fitting package, and use it to analyse the broadband spectra from the known ULX pulsars observed with the XMM-Newton and NuSTAR satellites. The model may also then be applied to the broader ULX population to investigate similarities/differences with the known pulsar ULXs, depending on progress. We may also be able to release the model for general use within the broader high-energy community.

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 the development of a new model, and subsequent analysis of X-ray spectra with this model; relatively basic programming will be required.

Useful references:

38. Gaia & Gaia-ESO: Defining the members of Open and Globular Clusters

| Supervisor I: Clare Worley (H24, ccworley) |
| Supervisor II: Anna Hourihan, Floor Van Leeuwen |
| UTO: Gerry Gilmore |

**Project summary:**
To compare the spectroscopic membership of the stars of the Gaia-ESO Survey open and globular clusters, with the astrometric membership of those clusters as derived from the Gaia Mission Data Release 2, in order to explore the definition of cluster membership and characterise the chemical and kinematic signatures of the Gaia-ESO Survey clusters in the context of the open and globular cluster systems of the Milky Way.

**Project description:**
Identifying the member stars of open and globular clusters is crucial for the accurate definition of the characteristics of cluster extent, chemical composition and age of those clusters. With this information the cluster system of the Milky Way can be examined for clues as to the formation and evolution history of our Galaxy. Astrometric cluster membership using the Gaia Mission Data Release 2 has been carried out for the clusters observed by Gaia-ESO Survey internal Data Release 5, for a number of which spectroscopic membership has also been defined. A comparison of these dataset will result in an optimal set of member stars for which the Gaia-ESO clusters can then be used to examine the cluster system formation and evolution history.

**Background:**
Open clusters represent the birth place of the majority of stars in the Milky Way disk and thus are some of the youngest and most enriched stars in the Galaxy. In contrast the globular clusters reside in the halo of the Milky Way and were formed on a similar timescale as the Milky Way, thus these stars are some of the oldest and least enriched stars in the Galaxy. However the commonality is that the stars within each type of cluster are co-eval within that cluster, and thus each cluster represents a point in the enrichment history of the Milky Way.

The chemical signatures of the stars in a cluster bear the chemical signature of the gas cloud from which the cluster formed, thus variations in chemical elements within a cluster are typically small. This means that the chemical history is retained even though eventually the kinematic history may be erased due to the migration of the cluster stars into the general disk population and thus interactions in the disk dampening out the kinematic signature of the cluster. Crucial to characterising the chemical signature of each cluster is clearly defining which stars are cluster members and which are not from the observed disk field.

The Gaia-ESO Survey is a high resolution spectroscopic survey of more than 100,000 stars in the Milky Way. The dataset samples the stellar populations of the disk, bulge and halo in order to measure the effective temperature, surface gravity and the chemical composition of each star. A key science goal of the Gaia-ESO Survey is the history of open clusters within the Milky Way (see G. Gilmore et al. 2012). The most recent catalogue available to the Gaia-ESO consortium is internal Data Release 5 (iDR5).
The Gaia Mission is an astrometric mission to measure parallaxes (and thus astronomers can derive distances) to more than 1 billion stars in the Milky Way, for which the most recent release is Data Release 2 (F. van Leeuwen et al. 2018).

The open clusters stars observed by Gaia-ESO are expected to be present (depending on quality assessment) with the Gaia DR2. Thus far the Gaia-ESO cluster membership has relied on the coordinates, radial velocities and metallicities of cluster stars all being consistent (Randich et al. 2018). However now with the high precision of Gaia coordinates, parallaxes and proper motions, Gaia DR2 astrometric cluster membership of the Gaia-ESO clusters has been carried out by F. van Leeuwen (private communication).

Comparing and combining these two definitions of cluster membership potentially will produce a refined cluster members sample, which can be used to investigate the cluster system as sampled by Gaia-ESO. This will allow intra- and inter-cluster comparisons looking at the distribution of the cluster chemical signatures with location in the Galaxy and also with age due to the fitting of isochrones. This range of measurements from two surveys that can be used to define membership can also be explored to deepen our understanding of what is a ‘member’ of a young stellar cluster.

Composite Hertzsprung-Russell diagrams for open clusters and globular clusters from Gaia DR2 are shown in Figures 1 and 2 respectively (Babusiaux et al. 2018). These show the stellar evolution branches, with the open clusters mainly populating the extent of the main sequence, while the globular clusters are dominated by giant stars.

*Figure 1: Composite HRD for 32 open clusters with colourmap of log(age) from Gaia DR2 (See Babusiaux et al. 2018, fig.2)*
Figure 2: Composite HRD for 14 globular clusters, with metallicity colormap from Gaia DR2 (see Babusiaux et al. 2018, fig 3).

Project details:

The project will use the open and globular cluster stellar samples of the Gaia-ESO Survey internal Data Release 5 (Randich et al. 2018) for which there are stellar parameters and chemical abundances, in combination with the astrometric membership dataset of the Gaia-ESO clusters as produced by F. van Leeuwen based on Gaia Data Release 2 (private communication). Cluster membership will be determined spectroscopically from Gaia-ESO data where not already available.

The two types of membership will be compared for each cluster to identify those stars defined as members by both or either method. Those stars not classified as members by both methods will be investigated further by looking at the other types of measurement available (signal-to-noise, radial velocities, errors, extinction) to attempt to understand the discrepancies.

Defining a clean membership list is a key goal of this project, the process of which includes exploring the range of membership indicators (measurements from both surveys) and thus also exploring the concept of what makes a star a member of a cluster.

Once a clean member list has been defined, each cluster will be characterised in terms of its chemical distribution for those elements that are available in the Gaia-ESO Survey, and also an age determination will be explored using isochrones fitting, starting with those provided by the analysis of F. van Leeuwen (private communication).

The open clusters and globular clusters systems will be explored in terms of cluster motion, chemical composition and location in the galaxy both separately and combined, as these are two system reflecting different timescales in the history of the Galaxy.
Skills required:
Basic programming in a language of preference (e.g. Python, Matlab)
Some familiarity with galaxy and cluster formation and evolution is desirable but not required.

Useful references:

General references:
(http://www.eso.org/sci/publications/messenger/archive/no.147-mar12/messenger-no147-25-31.pdf)
Gaia DR2 documentation, F. van Leeuwen et al. 2018,
(https://gea.esac.esa.int/archive/documentation/GDR2/index.html)
Gaia & Gaia-ESO: Characterising the Milky Way Field

Supervisor I: Clare Worley (H24, ccworley)
Supervisor II: Jason Sanders
UTO: Gerry Gilmore

Project summary:
To compare stellar parameters derived from Gaia astrometry and target catalogue photometry with stellar parameters derived from Gaia-ESO high resolution spectroscopy, thus identifying the strengths and weaknesses of each parameter set for this comprehensive stellar dataset of key Milky Way populations.

Project description:
The Gaia Mission and the Gaia-ESO Survey are two important projects for Galactic Archaeology as their extensive datasets contain samples with sufficient significance to allow for comparison to our theories of galaxy formation and evolution. This project combines the measurements from these two surveys for the Milky Way field sample of the Gaia-ESO Survey to provide a test case for understanding the extent and limitations of the sample and measurements, and then to scientifically exploit the combined data to characterise the stellar populations of the Milky Way disk.

Background:
The testing of galaxy formation and evolution models against observations requires extensive datasets that encompass both kinematic and chemical information for the range of stars that make up the stellar populations of the Milky Way.

The Gaia-ESO Survey is a high resolution spectroscopic survey of more than 100,000 stars in the Milky Way. The dataset samples the stellar populations of the disk, bulge and halo in order to measure the effective temperature, surface gravity and the chemical composition of each star. A key science goal of the Gaia-ESO Survey is the formation and evolution of the Milky Way disk populations in the greater context of galaxy evolution. (see G. Gilmore et al. 2012). The most recent catalogue available to the Gaia-ESO consortium is internal Data Release 5 (iDR5). The high resolution spectra that were observed for the Gaia-ESO Survey provide comprehensive chemical signatures for each star.

The Gaia Mission is an astrometric mission to measure parallaxes (and thus astronomers can derive distances) to more than 1 billion stars in the Milky Way, for which the most recent release is Data Release 2 (iDR2, F. van Leeuwen et al. 2018).

The key aspect of the Gaia-ESO Survey is goal to combine the derived chemical signatures with the kinematic information from Gaia (parallax and proper motion) for each star, thus tracing in both kinematic and chemical space the origins of these populations.
The combination of the recent Gaia Mission DR2, and the penultimate data release of the Gaia-ESO Survey (iDR5), now allow for this comparison in a significant way. The Milky Way field star programme was designed to provide the detail necessary to detect and distinguish any distinct populations within the Milky Way disk, in particular the existence of the thin and thick disks (Gilmore & Reid 1983). These populations have distinct chemical and kinematic attributes, and previously the Gaia-ESO survey has shown the chemical distinction, but now with Gaia the precise kinematic signatures can be explored.

However, both the spectroscopic and astrometric methods each have their strengths and weaknesses. This first comparison of parameters derived both ways must include an investigation of these strengths and weakness to understand for which regimes:

1. The stellar parameters of both methods agree within a small uncertainty;
2. The stellar parameters for which spectroscopy parameters prove to be more reliable than the astrometric/photometric parameters;
3. The stellar parameters for which astrometric/photometric parameters prove to be more reliable than the spectroscopy parameters.

Exploring the parameter space of these methods using the Gaia-ESO iDR5 Milky Way field star sample will be a first test of the robustness of the results from both projects, and a first look at the scientific impact of combining these two datasets.

Project details:

The project proposed here is to examine the Gaia-ESO iDR5 stellar parameters and the associated Gaia information for these stars for which the cross-match has already been carried out by J. Sanders. J. Sanders has also already calculated stellar parameters from the Gaia priors (parallax, proper motion) and target catalogue photometry (2MASS, VISTA) (Sanders & Das, 2018).

The stellar parameters derived from the Gaia priors are shown in Figure 1 as HR Diagrams with metallicity and age colour maps respectively.
Preliminary work is to become familiar with these datasets, and carry out basic comparisons of the two stellar parameters sets by producing key graphical diagnostics. These can be carried out in the programming language of choice (e.g. Python, Matlab).

Examples of such comparison are shown in Figure 2.

The following work is to characterise the differences in the stellar parameters, looking for the regimes in the stellar parameter space where the differences are significant and investigating by comparison to other measurements (signal to noise, extinction, radial velocities and errors) potential sources of the differences.

This phase may include statistical tests to quantify the significance of the agreement or disagreement in different regimes where appropriate.

Once a well understood sample of the Milky Way field stars with robust parameters is defined, this sample can be explored for the scientific aspects of the project. This part will include
combining the kinematic information from Gaia with the chemical information from Gaia-ESO to characterise the populations within the Milky Way disk.

Skills required:
- Basic programming skills in language of choice (e.g. Python, Matlab)
- Background knowledge of galaxy formation and evolution is desirable but not required.

Useful references:
- Gilmore & Reid 1983 ([link](http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1983MNRAS.202.1025G&amp;data_type=PDF_HIGH&amp;whole_paper=YES&amp;type=PRINTER&amp;filetype=.pdf))

General references:
- Gaia DR2 documentation, F. van Leeuwen et al. 2018, ([https://gea.esac.esa.int/archive/documentation/GDR2/index.html](https://gea.esac.esa.int/archive/documentation/GDR2/index.html))
40. Reassessing the dust-free class III stars in young star forming regions

Supervisor I: Mark Wyatt (H37, wyatt@ast.cam.ac.uk)
Supervisor II: Eugene Vasiliev (H53, vasiliev@ast.cam.ac.uk)
UTO: Mark Wyatt

Project summary:
This project will use kinematic data from the Gaia data release 2 (DR2) to reassess membership of nearby young star forming regions, and the fraction of stars in these regions with disks, to determine the median lifetime of protoplanetary disks which sets the timescale for planet formation.

Background:
When stars form they are surrounded by massive protoplanetary disks that contain significant quantities of gas and dust. It is within such disks that planets are thought to form. These disks last up to several Myr before being dispersed by some mechanism that is as yet undefined, but could be either photoevaporation or planet formation. The lifetime of these disks has been empirically determined by studying the fraction of stars in young star forming regions that have protoplanetary disks. All stars in the same region are assumed to have the same age, and the presence of a protoplanetary disk can be determined by looking for an infrared excess (class II stars have such excesses and class III stars do not). Plotting disk fraction as a function of age shows the median disk lifetime is a few Myr (see Fig. 1; Haisch et al. 2001; Wyatt 2008).

The protoplanetary disk lifetime provides a fundamental limit on the timescale on which planet formation processes must take place. However this is now being challenged by data from the Gaia satellite, which is surveying the whole sky, and in data release 2 (DR2) which was released in April 2018 (https://www.cosmos.esa.int/web/gaia/dr2), provides kinematic information (i.e., parallaxes/distances and proper motions) for over 10^9 sources down to 21st magnitude. Analysis of this data shows that membership of young star forming regions is not as well known as previously thought. Specifically, many of the class III stars that had been thought to be dust-free stars in these regions (i.e., stars which have already dispersed their protoplanetary disks) have parallaxes that show they are background stars (see Fig. 2; Manara et al. 2018). Class II stars are less likely to be affected, since infrared excesses are less common around background stars, so removing such contaminants will inevitably lead to an increase in the fraction of stars in any given region that have a disk, which in turn will increase the median protoplanetary disk lifetime. However, this may be offset by the fact that previously unknown class III stars can be identified in the Gaia data as being kinematically associated with the region.

What is clear is that a reassessment of the class III population is needed. This will have significant implications for our understanding of protoplanetary disk lifetimes and so of planet formation timescales. Also, class III stars are becoming ever more relevant as it is now possible with ALMA to trace the faint levels of dust around these stars that will help to identify and characterise the disk dispersal process (Wyatt et al. 2015).

Project details:
The project will involve taking lists of stars in nearby star forming regions from the literature and using Gaia DR2 data to determine whether the parallaxes and proper motions of class III candidates are consistent with membership in the region rather than being unassociated background objects. At a more advanced level, the full membership of the regions will be revised by searching for clustering within the Gaia DR2 catalogue. This should recover the original lists and add new
members. To assess the infrared excess these candidates would be cross-correlated with WISE,
Spitzer and Herschel information to identify protoplanetary disks (class II stars) and those without
dust (class III stars). This method would be developed by studying one region in detail and then
extended to further regions to address the protoplanetary disk lifetime question.

Figures:

Figure 1: Fraction of stars in star forming regions with different ages that have protoplanetary
disks (Wyatt 2008).

Figure 2: Gaia DR2 data for stars in the Lupus V star forming region that will be used to assess
membership – parallax (left), proper motion (middle) and colour-magnitude (right) (Manara et al.
2018).

Skills required:
Database querying, programming to run clustering algorithms.

References:
Wyatt 2008, ARAA, 46, 339
Wyatt et al. 2015, ApSS, 357, 103
41. **Bombardment of close-in super-Earths by comets scattered in by eccentric giant planets**

Supervisor I: Mark Wyatt (H37, wyatt@ast.cam.ac.uk)
Supervisor II: Sebastian Marino (H27, sm2132@ast.cam.ac.uk)
UTO: Mark Wyatt

**Project summary:**
This project will use N-body simulations of comets scattered by giant planets on eccentric orbits at a few au from a star to determine the fraction that impact super-Earth planets orbiting much closer in. Such planetary systems may be common (e.g., including one of the first exoplanets discovered by the recently launched TESS satellite), and this project will consider whether such impacts can have an observable consequence for the planet’s atmospheres.

**Background:**
Over the last 2 decades we have learnt that roughly half of stars host exoplanets that are detectable with current techniques. Most of these stars have super-Earths orbiting within 1au and ~5% have giant planets orbiting at a few au (e.g., Winn & Fabrycky 2015). Some have both types of planet and such systems may be common (Bryan et al. 2018). The TESS satellite is currently searching for transiting planets around bright stars with a view to following these up to characterise the planets’ atmospheres. One of the first TESS discoveries is of a super-Earth orbiting the star π Men (see Fig. 1; Huang et al. 2018) which also hosts a 10M\textsubscript{Jupiter} planet at 3au on an orbit with an eccentricity of 0.6 (see Fig. 1). The star also has a belt of comets orbiting at >40au (see Fig. 1; Sibthorpe et al. 2018). In the Solar System, comets are scattered in from the Kuiper belt, and although most are ejected by Jupiter, a sufficient number reach the Earth to have potentially delivered our atmosphere and oceans (de Niem et al. 2012). While giant planets on circular orbits cause a dynamical barrier preventing comets reaching the inner system (Wyatt et al. 2017), those on eccentric orbits can allow a significant quantity to penetrate into the inner regions (Frewen & Hansen 2014), where they may collide with any planets that may be present. The high energy of such collisions could have devastating consequences for any planetary atmosphere but could also replenish it with volatiles (Kral et al. 2018). It is thus possible that close-in planets in systems like that of π Men have undergone a level of bombardment much greater than the Earth, and that evidence of this could eventually be seen in its atmosphere. The dynamics of bombardment is such systems is, however, poorly characterised, and it is only now with systems like π Men in which constraints exist on the full planetary system that an appropriate system architecture can be contemplated.

**Project details:**
This project will involve running N-body simulations that follow the dynamical evolution of test particles (i.e., comets) in planetary systems like that of π Men. The simulations will be run using REBOUND (Rein & Liu 2012), and will use analysis techniques similar to those performed in Marino et al. (2018) and Frewen & Hansen (2014). The project would start using the parameters of π Men with test particles placed in the giant planet’s unstable region, and this would be expanded to consider particles originating further out that are scattered towards that giant planet, and would explore the effect of varying the various planet parameters. The effect of bombardment on the planet atmospheres would be characterised in a similar manner to the parameterisation of Kral et al. (2018).
Figures:

Figure 1: The planetary system of the star π Men (Huang et al. 2018; Sibthorpe et al. 2018): (Top) TESS light curve showing a 2.1R\textsubscript{Earth}, 4.8M\textsubscript{Earth} planet on a circular orbit with a 6.3day period. (Bottom left) Radial velocity observations showing a 10M\textsubscript{Jupiter} planet with a 5.7year period and eccentricity 0.6. (Bottom right) Spectral energy distribution showing the stellar photosphere at \~6,000K and excess emission in the infrared from a comet belt at \~40K.

Skills required:
Programming knowledge required. Attendance at the Planetary System Dynamics lecture would be beneficial for interpretation of the simulations.

References:
de Niem et al. 2012, Icarus, 221, 495
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

**Michaelmas 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 five projects, in rank order, should be handed to the Course Secretary by 12pm on the second Friday of Michaelmas Full Term (12 October 2018). 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 (16 October 2018). 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 (30 November 2018). 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 (12, 13, 14, 15 March 2019). 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.
Easter 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 17 April 2018. An eighth Supervision, to discuss the draft report, should take place no later than the first Tuesday of Easter Full Term (23 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 (30 April 2019). 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 18 June 2019 TBC.

Project reports may be collected from the Course Secretary after 9.30 am on Wednesday 19 June 2019.

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

<table>
<thead>
<tr>
<th>Name</th>
<th>Email</th>
<th>Phone</th>
<th>Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banerji, Manda</td>
<td>mbanerji</td>
<td>(3)37549</td>
<td>Kavli 19</td>
</tr>
<tr>
<td>Belokurov, Vasily</td>
<td>vasily</td>
<td>(3)37515</td>
<td>Hoyle 20</td>
</tr>
<tr>
<td>Booth, Richard</td>
<td>rab200</td>
<td>(7)60799</td>
<td>Hoyle 35</td>
</tr>
<tr>
<td>Bourne, Martin</td>
<td>mabourne</td>
<td>(7)46430</td>
<td>Kavli 08</td>
</tr>
<tr>
<td>Breedt, Elme</td>
<td>ebreedt</td>
<td>(7)66096</td>
<td>Hoyle 34</td>
</tr>
<tr>
<td>Busso, Giorgia</td>
<td>giorgia</td>
<td>(7)66603</td>
<td>Obs 22</td>
</tr>
<tr>
<td>Challinor, Anthony</td>
<td>a.d.challinor</td>
<td>(7)66659</td>
<td>Kavli 2</td>
</tr>
<tr>
<td>Clarke, Cathie</td>
<td>cclarke</td>
<td>(3)39087</td>
<td>Hoyle 10</td>
</tr>
<tr>
<td>Coulton, Will</td>
<td>wcoulton</td>
<td></td>
<td>K22</td>
</tr>
<tr>
<td>De Angeli, Francesca</td>
<td>fda</td>
<td>(3)37546</td>
<td>Obs 23</td>
</tr>
<tr>
<td>DeGraf, Colin</td>
<td>cdegraf</td>
<td>(7)46430</td>
<td>Kavli 8</td>
</tr>
<tr>
<td>Del Zanna, Giulio</td>
<td><a href="mailto:gd232@cam.ac.uk">gd232@cam.ac.uk</a></td>
<td>(3)37916</td>
<td></td>
</tr>
<tr>
<td>Diener, Catrina</td>
<td>cdiener</td>
<td>(7)66646</td>
<td>Obs 24</td>
</tr>
<tr>
<td>Efstathiou, George</td>
<td>gpe</td>
<td>(3)37530</td>
<td>Kavli 15</td>
</tr>
<tr>
<td>Evans, Wyn</td>
<td>nwe</td>
<td>(7)65847</td>
<td>Hoyle 50</td>
</tr>
<tr>
<td>Fabian, Andy</td>
<td>acf</td>
<td>(3)37509</td>
<td>Hoyle 54</td>
</tr>
<tr>
<td>Gaikwad, Prakash</td>
<td>pgaikwad</td>
<td>(3)37527</td>
<td>Kavli 18</td>
</tr>
<tr>
<td>Gilks, Avishai</td>
<td>agilkis</td>
<td>(7)60799</td>
<td>Hoyle 35</td>
</tr>
<tr>
<td>Gilmore, Gerry</td>
<td>gil</td>
<td>(3)37506</td>
<td>Hoyle 47</td>
</tr>
<tr>
<td>Gonneau, Anais</td>
<td>agonneau</td>
<td>(3)37504</td>
<td>Hoyle 21</td>
</tr>
<tr>
<td>Gonzalez-Fernandez, Carlos</td>
<td>cgonzal</td>
<td>(3)30896</td>
<td>APM A05</td>
</tr>
<tr>
<td>Gratton, Steven</td>
<td>stg20</td>
<td>(7)65849</td>
<td>Kavli 7</td>
</tr>
<tr>
<td>Haehnelt, Martin</td>
<td>haehnelt</td>
<td>(7)66671</td>
<td>Kavli 27</td>
</tr>
<tr>
<td>Halabi, Ghina</td>
<td>gmh</td>
<td>(3)66691</td>
<td>Hoyle 32</td>
</tr>
<tr>
<td>Hewett, Paul</td>
<td>phewett</td>
<td>(3)37507</td>
<td>Hoyle 19</td>
</tr>
<tr>
<td>Hodgkin, Simon</td>
<td>sth</td>
<td>(7)66657</td>
<td>Hoyle 39</td>
</tr>
<tr>
<td>Hourihane, Anna</td>
<td>aph</td>
<td>(7)66667</td>
<td>Hoyle 24</td>
</tr>
<tr>
<td>Irwin, Mike</td>
<td>mike</td>
<td>(7)64606</td>
<td>APM A1</td>
</tr>
<tr>
<td>Kama, Mihkel</td>
<td>mkama</td>
<td>(3)37504</td>
<td>Hoyle 36</td>
</tr>
<tr>
<td>Koposov, Sergey</td>
<td><a href="mailto:s.koposov@cmu.edu">s.koposov@cmu.edu</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lansbury, George</td>
<td>gbl23</td>
<td>(7)60793</td>
<td>Hoyle 51</td>
</tr>
<tr>
<td>Madhusudhan, Nikku</td>
<td>nmadhu</td>
<td>(7)66619</td>
<td>Hoyle 18</td>
</tr>
<tr>
<td>Marino, Sebastian</td>
<td>sm2132</td>
<td>(7)66653</td>
<td>Hoyle 27</td>
</tr>
<tr>
<td>McMahon, Richard</td>
<td>rgm</td>
<td>(3)37519</td>
<td>Hoyle 49</td>
</tr>
<tr>
<td>Meerborg, Daan</td>
<td>pdm</td>
<td>(7)46429</td>
<td>Kavli 6</td>
</tr>
<tr>
<td>Murphy, David</td>
<td>dmurphy</td>
<td>(7)65846</td>
<td>APM A05-2</td>
</tr>
<tr>
<td>Parry, Ian</td>
<td>irp</td>
<td>(3)37092</td>
<td>Hoyle 57</td>
</tr>
<tr>
<td>Pebody, Gudrun</td>
<td>gpebody</td>
<td>(7)66097</td>
<td>Hoyle 46</td>
</tr>
<tr>
<td>Pons, Estelle</td>
<td>pons</td>
<td>(7)60792</td>
<td>Hoyle 55</td>
</tr>
<tr>
<td>Reynolds, Chris</td>
<td>csr12</td>
<td>(7)66668</td>
<td>Hoyle 15</td>
</tr>
<tr>
<td>Sanders, Jason</td>
<td>jls</td>
<td>(3)37542</td>
<td>Hoyle 33</td>
</tr>
<tr>
<td>Sherwin, Blake</td>
<td><a href="mailto:sherwin@damtp.cam.ac.uk">sherwin@damtp.cam.ac.uk</a></td>
<td>(01223 766918</td>
<td>B1.02(Damtp)</td>
</tr>
<tr>
<td>Sijacki, Debora</td>
<td>deborasa</td>
<td>(7)66642</td>
<td>Kavli 17</td>
</tr>
<tr>
<td>Shorttle, Oliver</td>
<td><a href="mailto:os258@cam.ac.uk">os258@cam.ac.uk</a></td>
<td>(3)37515</td>
<td>Hoyle 20</td>
</tr>
<tr>
<td>Tout, Christopher</td>
<td>cat</td>
<td>(3)37502</td>
<td>Hoyle 61</td>
</tr>
<tr>
<td>Name</td>
<td>Username</td>
<td>Phone</td>
<td>Location</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>Vasiliev, Eugene</td>
<td>vasiliev</td>
<td>(3)30895</td>
<td>Hoyle 53</td>
</tr>
<tr>
<td>Walton, Dom</td>
<td>dwalton</td>
<td>(7)60793</td>
<td>Hoyle 51</td>
</tr>
<tr>
<td>Worley, Clare</td>
<td>ccworley</td>
<td>(7)66667</td>
<td>Hoyle 24</td>
</tr>
<tr>
<td>Wyatt, Mark</td>
<td>wyatt</td>
<td>(3)37517</td>
<td>Hoyle 38</td>
</tr>
</tbody>
</table>

Email: +*@ast.cam.ac.uk unless given otherwise