<table>
<thead>
<tr>
<th>#</th>
<th>Primary Supervisor(s)</th>
<th>Secondary supervisor</th>
<th>Assoc.UTO/supervisor</th>
<th>Project title</th>
<th>pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Auger, Matthew</td>
<td></td>
<td>McMahon, Richard</td>
<td>Einstein rings of strongly lensed QSOs: properties of AGN hosts at z~2 and new constraints on the lensing potential</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Banerji, Manda</td>
<td>Hewett, Paul</td>
<td>Hewett, Paul</td>
<td>Quasars and Friends: Exploring the environments of the most massive supermassive black-holes in the early Universe</td>
<td>2-3</td>
</tr>
<tr>
<td>3</td>
<td>Bonsor, Amy</td>
<td></td>
<td>Wyatt, Mark</td>
<td>Belts of asteroids and comets: do they survive around giant stars?</td>
<td>4-5</td>
</tr>
<tr>
<td>4</td>
<td>Bourne, Martin</td>
<td></td>
<td>Sijacki, Debora</td>
<td>AGN feedback: Quenching and triggering of star formation in disc galaxies</td>
<td>6-8</td>
</tr>
<tr>
<td>5</td>
<td>Hourihane, Anna</td>
<td>Breedt, Elme</td>
<td>Gilmore, Gerry</td>
<td>Improving visualisation of time-series and large data sets</td>
<td>9-10</td>
</tr>
<tr>
<td>6</td>
<td>Clarke, Cathie</td>
<td>Madhusudhan, Nikku</td>
<td>Clarke, Cathie</td>
<td>The ablation of planetesimals in gas giant planets formed through gravitational instability</td>
<td>11-12</td>
</tr>
<tr>
<td>7</td>
<td>Efstathiou, George</td>
<td>Gratton, Steven</td>
<td>Efstathiou, George</td>
<td>An inverse distance ladder approach to the Hubble constant</td>
<td>13-15</td>
</tr>
<tr>
<td>8</td>
<td>Fiacconi, Davide</td>
<td></td>
<td>Sijacki, Debora</td>
<td>Thermal instability in the circumgalactic medium of z~6 galaxies</td>
<td>16-18</td>
</tr>
<tr>
<td>9</td>
<td>Sijacki, Debora</td>
<td>Fiacconi, Davide</td>
<td>Sijacki, Debora</td>
<td>Spin alignment in circumbinary discs</td>
<td>19-21</td>
</tr>
<tr>
<td>10</td>
<td>Gilmore, Gerry</td>
<td>Worley, Clare</td>
<td>Gilmore, Gerry</td>
<td>Are the first stars hiding behind later pollution?</td>
<td>22-23</td>
</tr>
<tr>
<td>11</td>
<td>Halabi, Ghina</td>
<td></td>
<td>Hewett, Paul</td>
<td>The role of stellar evolution &amp; nucleosynthesis in the formation of white dwarfs: how updated stellar models may affect yields of novae explosions.</td>
<td>24-25</td>
</tr>
<tr>
<td>12</td>
<td>Hewett, Paul</td>
<td>Banerji, Manda</td>
<td>Hewett, Paul</td>
<td>Host galaxy properties derived from a statistical analysis of quasar spectra photometry</td>
<td>26-27</td>
</tr>
<tr>
<td>13</td>
<td>Hodgkin, Simon</td>
<td>Kennedy, Grant</td>
<td>Wyatt, Mark</td>
<td>A systematic search for transiting Exocomets</td>
<td>28-29</td>
</tr>
<tr>
<td>14</td>
<td>Juhasz, Atilla</td>
<td>Rosotti, Giovanni</td>
<td>Clarke, Cathie</td>
<td>Connection between planets and spiral arms in protoplanetary discs</td>
<td>30-31</td>
</tr>
<tr>
<td>15</td>
<td>Kama, Mihkel</td>
<td>Clarke, Cathie</td>
<td>Clarke, Cathie</td>
<td>Expanding the observational frontier of planet formation</td>
<td>32-33</td>
</tr>
<tr>
<td>16</td>
<td>Lansbury, George</td>
<td>Banerji, Manda</td>
<td>Fabian, Andy</td>
<td>The environments of supermassive black hole growth: studying the host galaxies of high energy X-ray AGN</td>
<td>34-35</td>
</tr>
<tr>
<td>17</td>
<td>Madhusudhan, Nikku</td>
<td>Hodgkin, Simon</td>
<td>Madhusudhan, Nikku</td>
<td>High-resolution spectroscopy of a hot Jupiter</td>
<td>36-37</td>
</tr>
<tr>
<td>#</td>
<td>Primary Supervisors(s)</td>
<td>Secondary Supervisor</td>
<td>Assoc. UTO/supervisor</td>
<td>Project title</td>
<td>Page(s)</td>
</tr>
<tr>
<td>---</td>
<td>------------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>---------------</td>
<td>---------</td>
</tr>
<tr>
<td>19</td>
<td>Parry, Ian</td>
<td>Irwin, Mike</td>
<td>Parry, Ian</td>
<td>What is the optimal primary mirror shape for a space telescope?</td>
<td>40-41</td>
</tr>
<tr>
<td>20</td>
<td>Pinto, Ciro</td>
<td>Fabian, Andy</td>
<td>Fabian, Andy</td>
<td>Extreme matter accretion onto black holes in ultraluminous X-ray sources and active galactic nuclei</td>
<td>42-43</td>
</tr>
<tr>
<td>21</td>
<td>Pinto, Ciro</td>
<td>Fabian, Andy</td>
<td>Fabian, Andy</td>
<td>The fight between cooling and heating in clusters of galaxies</td>
<td>44-45</td>
</tr>
<tr>
<td>22</td>
<td>Puchwein, Ewald</td>
<td>Kulkarni, Girish</td>
<td>Haehnelt, Martin</td>
<td>Seeing the cosmic web in Lyman-alpha emission</td>
<td>46-47</td>
</tr>
<tr>
<td>23</td>
<td>Reynolds, Chris</td>
<td>Pinto, Ciro</td>
<td>Reynolds, Chris</td>
<td>Ultra-fast outflows from tidal disruptions of stars by massive black holes</td>
<td>48-49</td>
</tr>
<tr>
<td>24</td>
<td>Rosotti, Giovanni</td>
<td>Clarke, Cathie</td>
<td>Clarke, Cathie</td>
<td>Grain growth in proto-planetary discs in binary systems</td>
<td>50-52</td>
</tr>
<tr>
<td>25</td>
<td>Rosotti, Giovanni</td>
<td>Juhasz, Atilla</td>
<td>Clarke, Cathie</td>
<td>Detecting the signatures of planet formation around low mass stars</td>
<td>53-54</td>
</tr>
<tr>
<td>26</td>
<td>Russell, Helen</td>
<td>Fabian, Andy</td>
<td>Fabian, Andy</td>
<td>The gravitational sphere of influence of the black hole at the centre of NGC 4472</td>
<td>55-56</td>
</tr>
<tr>
<td>27*</td>
<td>Sanders, Jason</td>
<td>Evans, Wyn</td>
<td>Evans, Wyn</td>
<td>Dynamical models of globular clusters</td>
<td>57-58</td>
</tr>
<tr>
<td>28*</td>
<td>Sanders, Jason</td>
<td>Evans, Wyn</td>
<td>Evans, Wyn</td>
<td>The shapes of globular clusters from Hubble photometry</td>
<td>59-60</td>
</tr>
<tr>
<td>29</td>
<td>Shorttle, Oliver</td>
<td>Madhusudhan, Nikku</td>
<td>Shorttle, Oliver</td>
<td>Volcanism on hot super-Earths: how and why?</td>
<td>61-62</td>
</tr>
<tr>
<td>30</td>
<td>van Lieshout, Rik</td>
<td>Wyatt, Mark</td>
<td>Wyatt, Mark</td>
<td>Sublimating exoplanetary material around white dwarfs</td>
<td>63-64</td>
</tr>
<tr>
<td>31</td>
<td>van Lieshout, Rik</td>
<td>Bonsor, Amy</td>
<td>Wyatt, Mark</td>
<td>Thermal emission from eccentric dust populations around white dwarfs</td>
<td>65-66</td>
</tr>
<tr>
<td>32</td>
<td>Walton, Dom</td>
<td>Lansbury, George</td>
<td>Fabian, Andy</td>
<td>The hunt for ultraluminous X-ray pulsars</td>
<td>67-68</td>
</tr>
<tr>
<td>33</td>
<td>Walton, Nic</td>
<td>Irwin, Mike</td>
<td>Irwin, Mike</td>
<td>Mapping galactic planetary nebulae with Gaia</td>
<td>69-70</td>
</tr>
<tr>
<td>34</td>
<td>Worley, Clare</td>
<td>Gonneau, Anais</td>
<td>Gilmore, Gerry</td>
<td>Carbon stars in the Gaia-ESO Survey</td>
<td>71-72</td>
</tr>
<tr>
<td>35</td>
<td>Wyatt, Mark</td>
<td>Bonsor, Amy</td>
<td>Wyatt, Mark</td>
<td>Modelling the stochastic accretion of differentiated asteroid fragments onto white dwarfs</td>
<td>73-74</td>
</tr>
</tbody>
</table>

APPENDIX

Project timetable format and Content
Criteria for Marking Project Report – oral and written
Contact Lists:
Supervisors (project # order) & Supervisors (alphabetical)

* only one of projects [27] and [28] will be allocated to a student
Introduction

This booklet contains descriptions of the individual projects available in the academic year -2018/2017. 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 2017
1. **Einstein Rings of Strongly Lensed QSOs:**

Properties of AGN Hosts at $z \sim 2$ and New Constraints on the Lensing Potential

**Supervisors:** Matt Auger, H40, mauger@ast.cam.ac.uk; Richard McMahon, rgm@ast.cam.ac.uk

**UTO:** Richard McMahon

**Background:** Strong gravitational lensing produces multiple images of high-redshift systems, allowing the total mass of the foreground lensing objects (typically massive galaxies or clusters) to be precisely inferred whilst also magnifying the background objects (typically quasars or star-forming galaxies) thereby allowing them to be studied in greater detail. In particular, observing lensed arcs and Einstein rings of multiply-imaged QSOs provides a method to break the dark matter/stellar mass degeneracy. In general, every measurement of mass beyond the Milky Way is sensitive to the total mass and cannot distinguish between dark matter and ‘normal’ matter (e.g., gas and stars). However, because QSOs are intrinsically very small, they are sensitive to mass distributions that themselves are also very compact – i.e., the stars in foreground lensing galaxies, an effect called *microlensing*. The amount of microlensing depends on the fraction of mass that is in stars, and therefore breaks the dark matter/stellar mass degeneracy (e.g., Bate et al. 2011). These lensed QSO host galaxies are also intrinsically of interest. In the local Universe, the masses of super-massive black holes are tightly correlated with the central stellar velocity dispersions and stellar masses of their host galaxies, possibly signalling a close connection between the growth of these black holes and the galaxies in which they reside. However, it is extremely difficult to see if these correlations exist at higher redshifts – when galaxies and their central black holes are assembling – because black hole masses can only be inferred for QSOs, but these outshine their host galaxies but orders of magnitude. Fortunately, for lensed QSOs the lensing magnification ‘pulls’ the flux of the QSO host galaxies out from under the light of the QSO, and the properties of the host galaxy can therefore be inferred (Peng et al. 2006; Ding et al. 2017; also see Figure below).

**This Project:** The purpose of this project is to quantify the properties of host galaxies associated with lensed QSOs. The highly-motivated Part III student will use *Hubble Space Telescope* and ground-based adaptive optics imaging to determine the presence of lensed arcs or rings for all known QSO lenses. The student will then use state-of-the-art modelling techniques to simultaneously infer the lensing potential and remove the QSO images to robustly determine the relative stellar and dark matter densities and get a clear view of the underlying host galaxy. Curiously, many lensed QSOs show no evidence for a host galaxy, and the student will therefore put limits on how large and massive these galaxies can be: are high-redshift QSO hosts anomalously small?

Keck AO image of PS J0630-1201, a lensed QSO at $z = 3.4$. Modelling and subtracting the QSO images A, B, and C shows evidence for a lensed arc that is the host galaxy of the QSO, as seen in the high-contrast image on the right.
2: Quasars and Friends: Exploring the environments of the most massive supermassive black-holes in the early Universe

Supervisor I: Manda Banerji (Kavli K19, mbanerji@ast.cam.ac.uk)
UTO: Paul Hewett (Hoyle H19; phewett@ast.cam.ac.uk)

Project summary:

Do supermassive black-holes in the early Universe reside within massive over-densities of galaxies? We will study the environments of a new population of dusty quasars at high redshift (e.g. Banerji et al. 2015). We will search for evidence for over-densities of star-forming galaxies around these quasars and compare their environments to other distant galaxy populations where such measurements have been made. For any over-densities that are detected, we will use multi-wavelength data to characterise the properties of the quasar companions.

Background:

Quasars sign-post accretion on to super-massive black holes residing at the centres of massive galaxies. Theoretical models predict that both black-hole accretion and star formation depend on environment with a significant proportion of such activity taking place in high-density environments that will evolve to form massive galaxy clusters and super-clusters today. Observational evidence in favour of such a scenario is accumulating. At high-redshifts, several quasars have been found to be part of significant over-densities (e.g. Capak et al. 2011, Decarli et al. 2017) although the numbers of such luminous quasars within such “proto-clusters” is still small (see Overzier 2016 for a review).

We have recently identified a new population of very luminous, very massive dusty quasars (e.g. Banerji et al. 2015, 2017), which represent systems where luminous accretion and prodigious star formation are simultaneously occurring. As such, these are the ideal test-beds for theories of structure formation, which predict that both massive star-forming galaxies and quasars should reside in some of the largest over-densities in the early Universe. The advent of new multi-wavelength wide-field imaging surveys, with both the area and depth necessary to detect over-densities at high-redshift, makes an observational test of the theory possible for the first time.

Project details:

We will use wide-field multi-wavelength data from new optical and near infrared imaging surveys to look for over-densities around a confirmed population of high-redshift dusty quasars. All of the imaging data necessary for the project has already been acquired. The student will primarily be working with the images as well as catalogues already produced from these images with information about source positions, fluxes and other galaxy properties. Statistical methods will be used to test whether the galaxy number counts in
the quasar fields are sufficiently different from blank fields. We will also make comparisons to “control fields” hosting other interesting populations of high-redshift galaxies.

Multi-wavelength data has been acquired in the quasar fields using a range of filters covering optical to infrared wavelengths. Using the colours of the galaxies around the quasars, the student will attempt to measure crude redshifts for the galaxies using a technique known as photometric redshift estimation. The aim is to test whether the galaxies lie at the same redshift as the quasar and are therefore part of the same overdensity. Spectral energy distribution fitting will also allow other properties of the companion galaxies e.g. star formation rates to be estimated if time permits.

![Image](image.png)

**Figure 1:** Over-density of galaxies around a z=5.3 quasar as seen in wide-field imaging data (Capak et al. 2011). Some of the contaminants e.g. lower redshift galaxies and stars with similar colours as the distant quasar are also marked.

**Skills required:**

The project is discovery based and well suited to a student interested in gaining experience in analysing large observational datasets to make new discoveries.

Relevant lecture courses: Introduction to Cosmology, Formation of Structure in the Universe

The student will be expected to write code in Python or IDL.

**References:**

3. Belts of asteroids and comets: do they survive around giant stars?

Supervisor I: Amy Bonsor Hoyle 31 abonsor@ast.cam.ac.uk
Supervisor II: Quentin Kral, Hoyle 31, qkral@ast.cam.ac.uk
UTO: Mark Wyatt, Hoyle 38, wyatt@ast.cam.ac.uk

Project summary:
Very little is known about the fate of belts of comets and asteroids when their host stars evolve to become giants. The aim of this project is to use data from the recent infrared full sky survey, WISE, to search for potential dusty Kuiper-like belts around giants, and determine how frequently they occur. How does sublimation influence these dust belts, as their host stars increase in luminosity?

Project description:
The aim of this project is to investigate the fate of comets and asteroids orbiting giant stars. Such dusty belts are best detected in the infrared, where their emission can be observed over and above the stellar emission. By using data from the recent infrared full sky survey, WISE, this project will investigate how frequently such dust belts occur around giant stars.

The collisional evolution of debris belts observed around main-sequence stars can be used to predict their fate when stars evolve. Bonsor & Wyatt, 2010, published a simple model that predicts the frequency of debris belts around giants stars, but neglected the effect of sublimation on the dust belts. One key aim of this work is to investigate whether sublimation increases the detectability of Kuiper-like belts, as predicted by Jura et al, 2004.

Background:
Dusty belts of comets and asteroids are commonly observed around main-sequence stars, similar to our Sun. Almost all such stars will one day evolve to become giant stars. What happens to the planetary systems?

Observationally, planetary material observed in the atmospheres of white dwarfs suggests that comets and/or asteroids survive to the white dwarf phase. Very little, however, is known about dust belts around giant stars. Whilst spectacular resolved images of debris belts around main-sequence stars are common, very few such detections exist for giant stars. Bonsor et al, 2013, 2014 provided Herschel images of 4 debris belts orbiting sub-giant stars, including KCrB, a planetary system with two (planetary) companions and a massive debris belt (shown in the figure). WISE is a recent full sky infrared survey perfectly placed for assessing the occurrence rate of dust belts.

Project details:
Task 1: Identify a sample of giant stars from the Tycho catalogue, using McDonald 2017 to identify stellar properties
Task 2: Search for WISE infrared data for the giant stars, and identify infrared excesses
Task 3: Check infrared excesses at multiple wavelengths for confusion with background galaxies
Task 4: Extend the model of Bonsor & Wyatt, 2010 to include WISE observations and make specific predictions for the sample of giant stars identified
Task 4: Compare the model to the observations, including various caveats for the infrared excesses that could be from giants stars losing mass and so forth
Fig: K CrB, a sub-giant with a debris disc. The left-hand plot shows the emission from the star at short wavelengths, and the excess emission from the dust belt at long wavelengths. The right-hand figure is a resolved image of the dust belt with Herschel.

Skills required:
The project involves a mixture of semi-analytic modelling and observations. Basic computing skills required. Attendance of the planetary dynamics lecture course would be useful, although not essential.

Useful references:

General references:
(List papers referred to in the project description)
4. AGN feedback: Quenching and triggering of star formation in disc galaxies

**Supervisor I:** Martin Bourne (K08, mabourne)  
**Supervisor II:** Debora Sijacki (K17, deboras)  
**UTO:** Debora Sijacki (K17, deboras)

**Project summary:** To perform hydrodynamical simulations of a disc galaxy in order to study the interplay between active galactic nuclei (AGN) feedback and star formation. In particular to constrain scenarios in which AGN feedback enhances or inhibits star formation.

**Project description:** We propose using hydrodynamical simulations of Milky way like galaxies to model the interplay of AGN feedback and star formation. Specifically, the student will consider the scenario in which AGN feedback, in the form of bipolar outflows, provides an external pressure that acts to compress the gaseous galaxy disc and hence potentially trigger star formation. A number of simulations will be performed using initial conditions with different disc gas fractions, and implementing AGN feedback with various powers. The simulations will then be analysed, for example to calculate the evolution of star formation rates, gas thermodynamic properties, locations of enhanced and inhibited star formation and galaxy morphology both during and after the AGN feedback event. This will allow the student to build up a picture of the regimes and physical mechanisms through which AGN feedback can promote star formation.

**Background:** The centres of most, if not all, massive galaxies host a supermassive black hole (SMBH) of mass $10^6–10^{10} \, M_\odot$. As SMBHs grow by accreting gas, vast amounts of energy can be released, resulting in the formation of an AGN. A fraction of the released energy can couple to the galaxy interstellar medium (ISM) in the form of radiation, winds and/or jets, which collectively are known as AGN feedback processes (Fabian 2012, King & Pounds 2015). Such feedback can heat gas, drive turbulence and clear gas out of galaxies as massive, powerful outflows. Traditionally, AGN feedback has been invoked as a source of negative feedback, which eventually inhibits further SMBH growth and quenches star formation by removing the supply of cold, dense gas (Bower et al. 2006, Croton et al. 2006, Sijacki et al. 2007, King & Pounds 2015). However, a number of theoretical models have suggested that under certain conditions AGN feedback may actually provide an additional channel of triggered star formation. Models proposed include AGN feedback sweeping up and compressing shells of gas to high densities that are able to cool efficiently (Ishibashi & Fabian 2012, Nayakshin & Zubovas 2012, Zubovas et al. 2013), hot, high pressure outflows enveloping and compressing massive gas clouds and filaments (e.g., Wagner et al. 2012, Zubovas & Bourne 2017) or AGN inflated bubbles providing an external pressure, which compresses galaxy discs (e.g., Silk 2013, Bieri et al. 2016, Zubovas & King 2016). It has been suggested that the later would provide an additional channel for recently observed inside-out disc-quenching (Tacchella et al. 2015) and would result in differences to the normalisation of the Kennicutt-Schmidt relation (Zubovas & King 2016).
Project details: The project would involve running a number of simulations of a Milky Way like galaxy. The student would be provided with initial conditions of galaxies with different disc gas fractions (1,5,10 and 20%), the simulation code and pre-defined setups to model bipolar outflows of different luminosities (0.1,0.5,1. & 2. L_{edd}) that are active for a fixed time. Depending on the disc gas fraction, the proposed simulations would have a gas mass resolution of ~400-8000 M⊙ and should each take ~1-3 days to run. The student would be provided with scripts to analyse the output of the simulations and as a minimum would be expected to consider the evolution of star formation rates and galaxy morphologies as a function of gas fraction and AGN luminosity. They would also be encouraged to consider other implications of the AGN feedback on star formation, including examining the specific regions of the galaxy in which AGN feedback inhibits or enhances star formation and how the location of these regions evolves with time. Based on the analysis the student should develop a hypothesis to explain the regimes in which AGN triggered star formation is important and for how long after the AGN has become dormant the feedback can continue to impact star formation. There is also the opportunity to additionally consider jet mode feedback and compare this to the bipolar outflows.

Skills required: Given the nature of this project, students should be comfortable with programming, particularly in C and a code suitable for analysing results, such as Python or IDL, while familiarity with Unix based systems is also desirable. Students should also be comfortable with the Part II astrophysical fluids course, while familiarity with the stellar dynamics and cosmology courses is desirable.

General references:

Useful references:


5. Improving visualisation of time-series and large data sets

Supervisor I: Anna Hourihane, H24, aph@ast.cam.ac.uk
Supervisor II: Elme Breedt H34, ebreedt@ast.cam.ac.uk
UTO: Gerry Gilmore, H47, gil@ast.cam.ac.uk

Project summary:
This project is to try ways of visualising astronomy data using geographical mapping tools. That is, terrain display (x,y,z) data, which we recognise as hills and valleys.

Project description:
Astronomy data is multiparameter (e.g. wavelength, flux, time ...) so can readily be mapped onto “contours” which our minds comprehend much better than a page of splodgy dots. A specific motivation is to develop an optimal way of visualising data collected for Gaia photometric transients (such as supernovae) – the Gaia Science Alerts1 - which are produced at the IoA, although the results from this project should be broadly applicable to other astronomical data.

Background:
Multi-colour time-series light curves and spectra are traditionally presented in astronomy in very crude ways. These often provide “information” which is so condensed as to require serious study to understand the content. Two examples are shown below in Figures 1 and 2.

Project details:
Fairly simple public-domain data visualisation capabilities exist – e.g. http://www.graphycalc.com/ among others. The goal of the project is to compare various tools and develop examples useful for astronomical data visualisation. The work will be to map astronomy data into terrain format, with simple data management – rotation, zoom, look over the hill, ... capabilities (see for example the apps of the British Geological Survey which implement this for geological terrain data²). The student will be expected to produce and compare a range of visualisation schemes. This will involve exploring various colour-mapping schemes. Familiarity with relevant computing skills is a pre-requisite - the project will not require any major coding but will require the exploitation of existing software such as virtual globe and publicly available image manipulation programs, such as Google Earth³, NASA World Wind⁴ and others. Simple, human-readable scripts developed in Keyhole Markup Language (kml, a type of Extensible Markup Language – xml – similar to Hypertext Markup Language – HTML) allow users to add their own geospatial data to the Google Earth canvas. To start with, mining of light curve data from astronomical transient or variable star

---

1  https://gaia.ac.uk/alerts
2  http://www.bgs.ac.uk/igeology/
3  https://www.google.com/earth/
4  http://goworldwind.org/
surveys (e.g. Palomar Transient Factory\(^5\), among others) will provide a test dataset. Light curve data will then be overlaid on a canvas such as Google Earth, which could be in segments of terrain or wrapped around a globe.

Knowledge of stellar properties such as temperature and luminosity and how they relate to observables such as colour and magnitude will be relevant, as will computing skills as described above. The initial phase of the project will be exploratory to assess several existing tools for suitability for adaptation for the purpose, which will then be developed into a range of visualisation tools.

Figure 1: Multi-colour light curve (left) and time series spectral data (right) of a supernova.

Figure 2: Follow-up photometric data of a transient detected by Gaia Alerts. The different colours and symbols indicate different photometric bands.

\(^5\) http://www.ptf.caltech.edu/iptf
6. The ablation of planetesimals in gas giant planets formed through gravitational instability

Project summary:

The project involves calculating the fate of rocky bodies ('planetesimals') falling into a recently formed giant planet with a view to finding whether these objects would be able to form a rocky core at the centre of the planet or would instead be destroyed ('ablated') by interaction with the envelope.

Project description:

This is a predominantly computational project involving the writing of some code from scratch but using a methodology set out and tested in the supervisors’ previous study of planetesimals falling into a planet with the structure of the present day Jupiter (Pinhas et al 2016). This study found that essentially no planetesimals were able to survive reaching the core. The young planets to be studied here (those formed by gravitational instability: see below) differ in several respects from the present day Jupiter, being notably less dense and cooler. This reduces the destructiveness of interaction with the envelope in two respects: lower density reduces so-called frictional ablation and lower temperatures reduce thermal ablation. It is therefore unclear whether or not planetesimals should be able to survive and form a rocky core in this context.

Background:

Recently it has become possible to place constraints on the atmospheric chemical composition of exoplanets (Madhusudhan & Seager 2009). Such measurements are mostly derived from spectroscopy of the atmospheres of massive irradiated planets (e.g., Madhusudhan et al. 2014). It is therefore now very timely to understand how chemical compositions of exoplanets can be used to place constraints on planet formation mechanisms.

The formation of planets is often discussed in terms of the ‘core accretion model’ (Mizuno 1980; Pollack et al. 1996) and its variants (Lambrechts & Johansen 2012) wherein a solid core assembles first. Whether such a rocky body goes on to form a rocky planet with little or no atmosphere or whether it instead ends up as the core of a giant gaseous planet depends on its success in capturing a massive gaseous envelope from its natal disc. A conceptually distinct mode of planet formation is one in which the the circumstellar disc itself fragments directly because of gravitational instability (henceforth, GI) to form a giant gaseous protoplanet. Such a mechanism can most naturally explain the small numbers of giant planets that have been imaged on wide orbits (Marois et al. 2008) although it has been argued that efficient inward migration would allow GI planets to also populate the inner disc close to their stars (Baruteau et al. 2011). Although the existence of rocky cores is a natural expectation in core accretion models, it is unclear whether or not this is expected in the GI scenario. To date, Helled & Schubert (2009) have computed how much solid material in the form of ‘planetesimals’ (km-scale rocky bodies) could be accreted by an infant planet formed through GI. They have not however addressed whether the accreted solid material would be ablated and mixed into the gas envelope or if it could travel intact to the centre and form a rocky core.
Project details:
The student will first set up a model for the structure of the protoplanet which is well described at this evolutionary stage by a polytrope. A code will then be written to model thermal and frictional ablation for planetesimals with a variety of compositions, following closely the methodology set out in Pinhas et al. (2016): PhD student Pinhas will be closely involved in assisting with the project supervision. Since the planet contracts with time and the flux of planetesimals thus also evolves, it will be necessary to explore the ablation issue using a sequence of polytropic models with different radii for the protoplanet.

Skills required:
The student should be able to solve differential equations numerically using a programming language of their choice. ‘Structure and evolution of stars’ course provides useful context for setting up the protoplanetary model. ‘Extrasolar planets’ course provides useful wider background.

Useful references:


General references:
Papers referred to in the project description
3. Mizuno, H., Formation of the Giant Planets 1980, Progress of Theoretical Physics, 64, 544-557
7. An Inverse Distance Ladder Approach to the Hubble Constant

Project summary:

Instead of using the usual forward distance ladder approach to measuring the Hubble constant, the student will investigate an inverse distance ladder based on geometric measurements of the cosmic microwave background (CMB) radiation and the baryon acoustic oscillation (BAO) scale. The main goal of the project is to investigate the sensitivity of an inverse distance ladder to theoretical assumptions concerning the background cosmology.

Background:

Ever since the discovery of the expansion of the Universe, measurements of the Hubble constant $H_0$ have proved to be controversial. To determine absolute distances on cosmological scales, the conventional, forward distance ladder, approach requires an absolute distance to nearby objects containing a `standard candle', observations of more distant objects containing similar standard candles, and further extrapolation to cosmological distances. At each stage, systematic errors may be present which can accumulate to give an erroneous value of $H_0$. The state-of-the-art applications of the forward distance ladder approach are presented in Riess et al (2011, 2016). However, the Riess et al determination of $H_0$ differs by $\sim 3.4\sigma$ from the value determined from observations of the CMB by the Planck satellite on the assumption of the inflationary $\Lambda$CDM model (Planck Collaboration, 2014, 2016). If true, this discrepancy would require new physics beyond that assumed in $\Lambda$CDM. However, there are many potential sources of systematic error in the forward distance ladder approach (Efstathiou, 2014). An alternative approach is to use purely geometrical measurements from the CMB and BAO scales to bootstrap from high redshift to low redshift, leading to an inverse distance ladder approach to determining $H_0$ (see Aubourg et al, 2015). The aim of this project is to carefully investigate the theoretical assumptions involved in extrapolating an inverse distance ladder to zero redshift for direct comparison with the local $H_0$ measurements of Riess et al.

Project details:

Figure 1 shows an application of the inverse distance ladder. The red and yellow points show $H(z)/(1+z)$ estimated from measurements of the BAO scale from the Baryon Spectroscopic Oscillation Survey (BOSS, Alam et al 2016, Bautista et al 2017). The blue point shows the local forward distance ladder measurement of Riess et al (2016). The shaded black line shows the $+/1\sigma$ range allowed by the Planck satellite, assuming an inflationary $\Lambda$CDM cosmology. The scope of the Part III project is as follows:

[1] The student should understand the data and theory behind Fig. 1.
Figure 1: The Hubble constant as a function of redshift $z$. The black shaded band shows the $+/-1\sigma$ range allowed by Planck assuming an inflationary $\Lambda$CDM. Illustrating the discrepancy with the Riess et al. measurement at low redshift.

[2] Assume that the $\Lambda$CDM cosmology is valid at recombination ($z \sim 1000$), i.e. any new physics manifests itself at low redshift. Parameterise the expansion rate of the Universe at low redshift by a polynomial (or other suitable expansion) in $(1+z)$. Find a best fit expansion that is consistent with the CMB, BAO and Type Ia supernova magnitude redshift relation (Betoile, 2014).

[3] Assess whether the results are consistent with the Riess et al. measurements.

[4] Investigate the impact of new physics at $z \sim 1000$ (e.g. additional relativistic species).

[5] Investigate the prospects for improving the inverse distance ladder with improved BAO measurements from new galaxy surveys such as DESI and Euclid.

[1]-[3] form the core of the project. [4] may be possible on the timescale of the project depending on how quickly the student is able to master Monte-Carlo-Markov Chain (MCMC) computations. A detailed analysis of [5] is almost certainly beyond the scope of the project, but a short qualitative analysis should be possible.

Skills required:

The student should have attended courses in Cosmology and General Relativity. The core of this work will require running COSMOMC (a publicly available MCMC code) which is written in Fortran90. Inability to understand COSMOMC would be a severe handicap. The student would need to be able to manipulate the Type Ia supernovae data.
References:

Aubourg etal 2015, PRD, 92, 13516.
8. Thermal instability in the circumgalactic medium of z~6 galaxies

Supervisor I: Davide Fiacconi (Room K16, email: fiacconi@ast.cam.ac.uk)
Supervisor II: Debora Sijacki (Room K17, email: deboras@ast.cam.ac.uk)
UTO: Debora Sijacki (Room K17, email: deboras@ast.cam.ac.uk)

Project summary:
The growth of galaxies is dictated by the availability of fresh gas that eventually forms stars. This is regulated by the interplay between gas accretion from cosmological cold flows and gas cooling within the dark matter halo on one hand, and virial shock heating and stellar/AGN feedback on the other hand. The goal of this project is to study the contribution of thermal instability to this baryon cycle in a typical high redshift galaxy from a state-of-the-art cosmological simulation.

Project description:
The goal of the project is to study the role of thermal instability in the transport of gas from the circumgalactic medium (CGM) to the central galaxy. The student will analyse the outputs of two versions of a cosmological simulation that focuses on the early assembly (z~6) of a present day elliptical galaxy in a group. The student will measure the relative role of radiative cooling on the state of the gas to determine whether thermal instability plays a significant role in maintaining a multi-phase CGM and in providing gas to be accreted on to the central galaxy.

Background:
According to the current cosmological paradigm, the condensation of baryons at the centre of massive dark matter haloes is instrumental for the formation of galaxies. Gas cools radiatively and settles down at the bottom of the halo potential well where it eventually forms stars (White & Frenk 1991). This process is regulated by different mechanisms at large and small scales. At large scales, cold gas can flow along dense filaments towards the central galaxies of low mass haloes (≤10^{11} M_\odot, Keres et al. 2005, 2009), and otherwise shocks at the halo virial radius and reaches virial equilibrium in larger systems (Dekel & Birnboim 2006), producing a pressure-supported CGM. Closer to the galaxy, the gas is denser and radiative cooling becomes more efficient; the latter may be counterbalanced by the energy injected via supernova explosions and/or by feedback from active galactic nuclei (AGN).

Even if the CGM can exist in global thermal stability, local instabilities in the CGM may occur owing to perturbations induced by the mixing of material outflowing from the central galaxy, wakes induced by the infall of smaller galaxies or by mergers, and further inflow from cosmological filaments. As radiative cooling depends on the gas density and temperature, local thermal instability is expected to develop in regions where the cooling timescale is comparable or shorter than the the free-fall timescale to the centre of the halo (McCourt et al. 2012, Sharma et al. 2012). This can foster the formation of cold clouds within the CGM, which can then fall through the surrounding hotter gas onto the galaxy (Voit et al. 2015a,b), as shown in Figure 1 below. This multiphase structure can, in principle, be detected by MUSE and ALMA at lower redshifts (Borisova et al. 2016).

Project details:
This is a theoretical project based on the analysis of cosmological simulations. The student will be provided with the snapshots of “Ponos” (Fiacconi et al. 2017), a zoom-in simulation performed with the smoothed-particle hydrodynamics (SPH) code Gasoline, focussing on a typical z~6 galaxy. Specifically, the student will use two versions of the simulation: (i) the original version, performed...
with an “old” SPH implementation, and (ii) a new version, performed with a “modern” SPH implementation.

- Initially, the student will learn the foundations of the theory of galaxy formation, the physics of the circumgalactic gas, including thermal instability, and familiarise with the characteristics of the runs.
- The student will use the Gasoline code to calculate in post-processing the cooling/heating rates used in the simulation.
- The student will use the pynbody package to read in the snapshots and the auxiliary files and to calculate the cooling and the free-fall time of the gas.
- The student will track the gas particles and the ratio between the timescales above to understand the role of thermal instability in the evolution of the circumgalactic gas (see figure below).
- The student will compare the results between the two simulations, assessing the numerical impact of the adopted methods.

Figure 1: Density (top row) and density contrast (bottom row) of thermally unstable gas in a vertical gravitational field. From left to right, the plots show the progressive increase in instability as the ratio between the cooling time and the free fall time decreases. Figure from McCourt et al. (2012).

Skills required:
The student should have good knowledge of C and Python programming. The Part II courses “Astrophysical Fluid Dynamics”, “Physics of Astrophysics”, and “Introduction to Cosmology” are required, while the Part III courses “Astrophysical Fluid Dynamics”, “Cosmology”, and “Galactic Astronomy and Dynamics” are desirable.

Useful references:
- Effect of thermal instability on the host star formation: Voit et al., 2015a, Nature, 519, 203
- More on thermal instability and host star formation: Voit et al., 2015b, ApJL, 808, 5
• **Ponos simulation paper**: Fiacconi et al., 2017, MNRAS, 467, 4080

General references:
• **Cold flows vs. shock heating**: Dekel & Birnboim, 2006, MNRAS, 368, 2
• **Galaxy Formation and Evolution** (Chapter 8), Mo, van den Bosch, and White, 2008, Cambridge Un. Press
9. Spin alignment in circumbinary discs

Project summary:
During their late evolutionary stages, supermassive black hole (SMBH) binaries are surrounded by a gaseous circumbinary disc. The interaction between the binary and the disc makes the binary separation shrink and feeds the SMBHs with inflowing gas. Gas accretion grows the BH masses and modifies the amplitude and orientation of the BH spins. The goal of this project is to study this process by means of hydrodynamical simulations of some representative cases, assessing the interplay between spin alignment and binary migration.

Project description:
The goal of the project is to study the alignment between the spins of the two SMBHs as a consequence of gas accretion during part of their inspiral. The student will run a few idealised simulations of a SMBH binary surrounded by a circumbinary disc for relevant parameters, e.g. prograde vs. retrograde, circular vs. eccentric orbits, or coplanar vs. misaligned, and will analyse them to understand which conditions favour spin alignment over orbital decay and viceversa.

Background:
When two gas-rich galaxies merge, their SMBHs spiral in towards the centre of the remnant owing to dynamical friction against the gaseous background (Colpi 2014; Bogdanovic 2015). Once their separation reaches a few pc, they form a SMBH binary, i.e. a gravitationally bound pair of SMBHs orbiting each other. Such a binary is usually embedded in a gaseous disc. As the mass enclosed by the binary orbit becomes roughly the binary mass itself, the SMBHs can clear up a cavity in the gas, forming a circumbinary disc (Cuadra et al. 2009; Farris et al. 2014). Then, the binary and the circumbinary disc interact through accretion and gravitational torques, exchanging mass and angular momentum. The SMBHS separation slowly reduces until the binary begins to emit gravitational waves that extract orbital energy and eventually lead the system to coalesce in a single SMBH.

During this process, the SMBH masses grow because of accretion; at the same time, accretion can modify the magnitude and orientation of the BH angular momenta, customarily named "spins" (King et al. 2005; Perego et al. 2009). Understanding the orientation of the spins in the proximity of the final coalescence is of fundamental importance. Indeed, their configuration sets the occurrence and the amount of a recoil kick after the emission of gravitational waves and the coalescence. The gravitational recoil kick can be as large as several 1000 km/s in the most extreme cases, potentially ejecting the remnant SMBH from its host. Moreover, knowing the spin configuration may also impose some constraints on the binary formation process, as for the recent aLIGO detections in the context of stellar BH binaries (Abbot et al. 2016A; 2016b; 2017).

Project details:
This is a theoretical project strongly based on numerical simulations. The student will use the Arepo code (Springel 2010), which incorporates a model for BH spin evolution developed in house, and will be provided with the initial conditions to run the simulations.

- Initially, the student will learn the foundations of the current theory of black hole spin-disc coupling and migration in circumbinary discs, as well as some basics of galaxy evolution.
• The student will familiarise with the code and will run a small suite of simulations (see Figure below) on the University HPC facilities.
• The student will analyse the simulations, interpreting them also on grounds of simple analytical understanding, e.g. measuring and comparing the timescales for spin alignment and orbital decay in different cases.

Evolution of the surface density of a self-gravitating circumbinary disc around a 1:3 SMBH binary. Time is in units of the binary orbital period. Figure taken from Cuadra et al. (2009).

Skills required:
The student should have good knowledge of C and Python programming. The Part II courses “Astrophysical Fluid Dynamics” and “Physics of Astrophysics” are required, while the Part III courses “Astrophysical Fluid Dynamics”, “Dynamics of Astrophysical Discs”, and “Galactic Astronomy and Dynamics” are desirable.

Useful references:
• Self-gravitating circumbinary discs: Cuadra et al., 2009, MNRAS, 393, 1423

General references:
• Theoretical review on SMBH binaries: Colpi M., 2014, SSRs, 183, 189 (arXiv:1407.3102)
• Observational review on SMBH binaries: Bogdanovic T., 2015, ASSPs, 40, 103 (arXiv:1406.5193)
• *LISA paper:* Amaro-Seoane et al., 2013, GW Notes, 6, 4 (arXiv:1201.3621)
• *aLIGO detections:*
  ○ Abbot et al., 2016a, PRL, 116, 61102
  ○ Abbot et al., 2016b, PRL, 116, 241103
  ○ Abbot et al., 2017, PRL, 118, 221101
10. Are the first stars hiding behind later pollution?

Supervisor I: Gerry Gilmore (H47, gil@ast.cam.ac.uk)
Supervisor II: Clare Worley, (H24, ccworley@ast.cam.ac.uk)
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 stars, 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.

Refs:
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 POIII stars Johnson 2015 MNRAS 453.2771
11. The role of stellar evolution & nucleosynthesis in the formation of white dwarfs: how updated stellar models may aff yields of novae explosions.

**Supervisor:** Ghina Halabi, Hoyle Building H32, email: gmh@ast.cam.ac.uk  
**UTO:** Paul Hewett, Hoyle Building H19, email: phewett@ast.cam.ac.uk

**Background**

The synthesis of light and intermediate-mass elements can take place during explosive stellar events. One astrophysical site where such processes can occur is classical nova. These are caused by mass transfer episodes from a main sequence star onto a degenerate oxygen-neon (ONe) or carbon oxygen (CO) white dwarf via Roche lobe overflow. This material possesses angular momentum, forms an accretion disc around the white dwarf and a fraction of which spirals in and piles up on the white dwarf surface. This results in repeated thermonuclear runaways that explosively eject about an Earth mass of matter into the interstellar medium. So novae are important contributors to the chemical evolution of the Galaxy.

To study the nova contribution to the Galactic chemical content quantitatively we must use state-of-the-art stellar models with the correct input physics and initial stellar conditions. The white dwarfs are the end points of complex stellar evolution of intermediate mass stars through their main sequence, red giant, core helium burning, asymptotic giant branch and possibly carbon burning phases. Being in binary systems these progenitor stars also experience a variety of unusual mass-loss events.

The student will learn how to use the Cambridge stellar evolution code STARS to evolve a representative selection of stars to the white dwarf phase, both single and in binary systems, using an updated nuclear reaction rates network. The student will then vary the initial chemical abundances in the code and investigate how that changes the chemical composition of ONe white dwarfs. This may substantially effect the nucleosynthesis during subsequent nova explosions hosted by an ONe white dwarf depending on the surface composition left in the white dwarf. Equally interesting here would be a null result if the stellar evolution to the white dwarf can erase memory of the initial compositions.

This alone would constitute sufficient work and results for the part III project but, for the more able student, the models can be fed into the state-of-the-art hydrodynamic code SHIVA, extensively used in the modelling of stellar explosions (e.g., classical novae, X-ray bursts) in a collaboration with Jordi Jose in Universitat Politcnica de Catalunya (UPC) Barcelona to investigate the effect of the updated abundance composition on nova explosion yields.

The project thus entails sufficient understanding of the underlying physics and provides excellent opportunity for the student to learn about stellar evolution and nucleosynthesis.

**Related Courses**

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.

**Nature of the Project Work**

Computational.
* Learn how to use the Cambridge STARS stellar evolution code in both its single and binary star modes.
* Understand and model the evolution of intermediate-mass stars from the ZAMS to the white dwarf phase.
* Vary the initial chemical abundances in the code and investigate how that changes the chemical composition of the white dwarfs.

References
12. Host galaxy properties derived from a statistical analysis of quasar spectra and photometry

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 DR12 data releases. Catalogues of low-ionisation absorbers due to singly ionised magnesium (MgIIλλ2796,2803) in gas associated with host galaxies, or outflowing material from the quasar, are available for the DR7 and DR12 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 DR12 web pages: http://www.sdss.org/dr7/ and http://www.sdss.org/dr12/
Joshi et al. arXiv:1706.03975 – quantifies the [OII]-emission star-formation for absorbing systems that are not directly associated with quasars, important reference/control information.
13. A Systematic Search for Transiting Exocomets

Supervisor I: Simon Hodgkin (H39, sth@ast.cam.ac.uk)
Supervisor II: Mark Wyatt (H38, wyatt@ast.cam.ac.uk)
Supervisor III: Grant Kennedy (Warwick/IoA)
UTO: Mark Wyatt (H38, wyatt@ast.cam.ac.uk)

Project summary:
The aim of the project is to develop an automated method to search for comet-like transits in photometric time series data, and apply it to archival Kepler data.

Background:
There has long been interest in whether comets orbit other stars, which would provide evidence for processes similar to those that occurred during the formation of the Solar System. One comet type of particular interest is those that pass close to the star on eccentric orbits; these could deliver water to habitable planets, replenish exo-Zodiacal dust clouds, and be a source of extinction-level planetary impacts.

The first clues that such comets do orbit other stars were discovered before the first extrasolar planets, seen as time-variable spectroscopic signatures towards the young star beta Pictoris (Ferlet et al. 1987). More recent evidence was revealed by the Kepler space mission, which observed a series of unusual dips in the light curve of the star KIC 8462852 (a.k.a. Tabby's star, Boyajian et al. 2016). Finally, a new study by Rappaport et al. (2017) found evidence for comet like dips in the light curves of KIC 3542116 and KIC 11084727 (see Figure 1). The light curves of these last two stars show the same characteristic shape that was predicted by Lecavelier Des Etangs et al. (1999), and thus provide strong evidence for the transits of large exocomets.

Fig 1: Figure 3 from Rappaport et al. (2017), showing sections of the light curve where comet-like dips are seen for KIC 3542116.
An astonishing aspect of the Rappaport et al. study is that they studied about 200,000 light curves by eye. The fact that the events all have a similar shape; a sharp "ingress" and a shallow "egress", as would be expected for a comet with a large tail, suggests that these events should be easily recovered by a carefully constructed computational algorithm. An obvious example is a "matched filter", which would simply try to fit a comet-like shape at every point in a given light curve, and note stars for which a significant detection was made. More complex methods may also be useful, for example a machine learning approach that uses synthetic light curves of simulated comet transits as a training set. Aside from Kepler, many time-series surveys are ongoing (K2, NGTS), or are coming in the future (e.g. TESS, PLATO), so the methods used here could be applied to many other extant and future datasets.

Project details:
The goal of this project is to use an automated approach to recover the comet-like transits discovered in archival Kepler data by Rappaport et al (2017). By using a systematic approach, confidence in the results will be higher than for an approach that is subject to human error and not necessarily repeatable. Of course, new systems that show similar events may also be discovered. Several possible approaches are noted above, and considering and experimenting with these and other methods will be an important part of the project.

Skills required:
The project will primarily use computational methods to explore the Kepler data, so some knowledge of programming would be beneficial. Attending the Planetary System Dynamics lectures will help understand the dynamics of comets, but is not essential.

References:
14. Connection between planets and spiral arms in protoplanetary discs

**Supervisor I:** Attila Juhász (H22, email: juhasz@ast.cam.ac.uk)
**Supervisor II:** Giovanni Rosotti (H21, email: rossotti@ast.cam.ac.uk)
**UTO:** Cathie J. Clarke (H10, email: cclarke@ast.cam.ac.uk)

**Project summary:**

One of the most striking observational result of planet formation studies in recent years was the discovery of spiral arms in protoplanetary accretion discs around young stars, where planets are believed to form. It is known from theoretical models that young forming planets, embedded in their parental disc, launch spiral density waves in the disc. Thus one of the most compelling explanations for the presence of the observed spirals is that they are driven by young forming planets. However, so far no direct observational proof exists for this scenario, as such young planets are extremely challenging to detect due to the contrast between the planet and the surrounding disc. The goal of this project is to test whether the observed spirals could be driven by planets and to study the connection of such planets to known population of exoplanets around main-sequence stars. The basic idea is to make predictions for the occurrence rate of planet-induced spirals in protoplanetary discs. The comparison of the calculated detection rate to the observed one will shed light on whether the detected spirals could be driven by young planets which will evolve to a known population of exoplanets.

**Background:**

Planets form in protoplanetary accretion discs around young stars. These discs consist of dust and gas and form as a natural by-product of the star formation process. They are typically a few hundred AU in radius and contain a mass of characteristically about 1% of that of the central star. The size, composition and structure of these discs can reveal important information about where, when and how planets form. For this very reason protoplanetary discs were in the focus of a vast amount of theoretical and observational studies. In recent years, the newest generation instruments made it possible to spatially resolve these discs in nearby star-forming regions and study their structure in detail. One of the striking discovery of these observations were the detection of spiral arms in protoplanetary discs in near-infrared scattered light [e.g. 1,2]. These spirals show similar morphology, with two symmetric arms, a pitch angle of about 15°–30° and a contrast of a few tens of percent over the background disc (see Figure 1). The observed spirals are located at several tens of AUs to over a hundred AU from the central star.

An exciting explanation for the presence of these spirals is that they are driven by young forming planets embedded in the disc [e.g. 3,4]. It is known from theoretical models that planets embedded in gaseous discs can excite spiral density waves at Lindblad resonances both inwards and outwards of their orbit. These spirals play an important role in the angular momentum transfer between the disc and the planet, and thus in the migration of the planet within the disc. Observations of planet-driven spirals will not only reveal the presence of embedded planets, but could also help us to understand planetary migration, which is a long standing problem in planet formation theory. Even though the planet scenario is very compelling there could be other explanations for the presence of the observed spirals, including for instance gravitational instability [e.g. 5], which would not require a planet in the disc.

**Project details:**

The only direct way to prove that the spirals observed in near-infrared images of protoplanetary discs are driven by embedded planets is to detect the planets themselves. Unfortunately this was not possible so far, due to the contrast limitation of even current state-of-the-art instruments on the largest telescopes. There are, however, also indirect ways to study the connection between embedded planets and spirals. Here we take a statistical approach to test of the occurrence rate of the observed spirals is compatible with the distribution of planet masses and semi-major axes predicted by planet formation theories.
Figure 1: Near-infrared polarised intensity images of spirals in the protoplanetary disk of HD 135344 B (left, from Stolker et al. 2016) and MWC 758 (right, from Benisty et al. 2015) taken with SPHERE on VLT.

To estimate the detection rate of planet driven spirals in near-infrared images of protoplanetary discs we will calculate synthetic images using the radiative transfer code RADMC-3D. The two most important parameters for the detectability of planet-driven spirals are the mass and the orbital radius of the planet, which we will take from population synthesis models of planet formation. These models were tuned to reproduce the observed distribution of known exoplanets around main-sequence stars, which are the end phase of the planet formation process. Once the mass and orbital radius of a planet is known we will select the corresponding model from a library of hydrodynamic simulations of protoplanetary discs with embedded planets, prepared by the supervisors. Once the density structure is known we can use the radiative transfer code to calculate images at near-infrared wavelengths. Finally we will degrade the resolution of the images to a level similar to the observations before studying the detectability of the spirals in the image.

By calculating an ensemble of models for a distribution of planet mass and semi-major axes drawn from the population synthesis models we can make a prediction for the detection rate of spirals driven by planet from the planets predicted by these models. We can then compare this to the statistics form the observations.

Skills required:
This project requires some programming/scripting skills in Python and running simulations in Unix/Linux environment.

Useful references:
Website of RADMC-3D: http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/
Python module for RADMC-3D http://www.ast.cam.ac.uk/~juhasz/radmc3dPyDoc/tutorial.html

General references:
15. Expanding the observational frontier of planet formation

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

Supervisor II: Dr Giovanni Rosotti, (H21, email:rosotti@ast.cam.ac.uk)

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

Project summary: Most of our knowledge of planet formation is derived from planet-forming disks around young stars within a few hundred parsecs of the solar system. This limits us to a narrow range of conditions such as initial metallicity. In this project, you will explore the use of the millimetre interferometer, ALMA, for studying faint protoplanetary disks at unprecedented distances from the Sun.

Project description: The two main components will be to simulate ALMA observations using the tools available in its accompanying software, CASA (which uses python), and to use physical or chemical models and imaginatively explore the possible science yield from studying faint and poorly resolved disks at larger distances. The project will form part of the foundation of an observational proposal for ALMA Cycle 6.
Background: The study of exoplanets and life’s origins is in full swing. The formation of planets is a major part of the chain of events which we must understand. While the ALMA interferometer has recently opened up an unprecedented combination of sensitivity and spatial resolution in the domain of (sub-)millimetre astronomy and yielded many important discoveries in planet formation, thus far it has been applied to nearby star-forming regions. You will study how ALMA can be applied to protoplanetary disks at an order of magnitude larger distance; and how key disk parameters may differ from the current sample of systems.

Project details:
You will do the first round of estimations of what can or cannot be detected analytically. The precise goals of the next stage will be determined based on the initial results. From there on, a key tool will be the ALMA observation simulation and data processing software, CASA. You will run simulations of how well ALMA can detect or spatially resolve well-known nearby disks at larger distances. This exercise will also be done with disk models as input.

The first data you will explore will be continuum emission. Determine the importance of local and extragalactic source confusion on a region-by-region basis, and how much that will limit our ability to detect disks and determine their parameters such as dust mass, size, and spectral index. You will produce synthetic observations and analyse these to determine how strongly the disk properties can be constrained. Arriving at a scripted workflow to produce the observations and to extract observables from them is where we expect most of the technical work effort to go. This will require both python scripting and becoming familiar with millimetre-wavelength telescopes and data.

There is also great interest in emission from bright, abundant gas species. Carbon monoxide (CO) is a prominent example. If the initial results are promising in terms of continuum emission detectability, you will also investigate the detectability of gas lines.

If the results are encouraging, the next and more creative part of the project will be where you will look at what range of science questions can be answered by studying planet-forming disks at unprecedented distances. Some examples of these are the abundance of refractory dust (the gas-to-dust ratio) and how it may affect disk mass, dissipation/planet formation timescales, etc.

A potential outcome is to provide simulations and contribute significantly to the science case of an ALMA proposal for the upcoming Cycle 6 Call for Proposals, due in late April, 2018. You can improve upon our initial list of candidate regions and specific targets to find the best feasibility plus science yield combinations. If this goes well and there is time, you can apply the same workflow to determine what other high-end and future telescopes such as EVLA, James Webb, LOFAR, or SKA could contribute to the study of disks at super-kiloparsec distances.

Skills required:
Scripting/programming with Python, or willingness to learn it once you begin, is essential.
Useful references:
and the Wikipedia article on ALMA
16. The environments of supermassive black hole growth: studying the host galaxies of high energy X-ray AGN

Supervisors: George Lansbury, Office: IoA H51, email: gbl23@ast.cam.ac.uk
           Manda Banerji, Office: Kavli K19, email: mbanerji@ast.cam.ac.uk
           UTO: Andy Fabian, Office: H54, email: acf@ast.cam.ac.uk

Background

Active galactic nuclei (AGN) are the energetic sites of rapid supermassive black hole (SMBH) growth (via accretion of matter) at the centres of galaxies (see Figure 1). Every massive galaxy in the Universe has, at some point in their lifetime, shone brightly as an AGN. Furthermore, correlations between the properties of SMBHs and their host galaxies imply a close connection between AGN activity and star formation (e.g., Kormendy & Ho 2013). At a given cosmic epoch, however, only a fraction of galaxies host AGN activity. Why is this? Do AGN live in a special galaxy environment, conducive to the fuelling of SMBH growth (e.g., Brandt & Alexander 2015, Section 5)? Are all AGN intrinsically similar, or are different classes associated with different galaxy environments?

To address the above questions, this project will aim to investigate the host galaxy properties of AGN identified at high X-ray energies by the NASA mission NuSTAR. A breakthrough has been provided by NuSTAR as it is the first space telescope able to focus high energy (E > 10 keV) X-rays. The telescope therefore provides a unique and unbiased sample of AGN (e.g., Lansbury et al. 2017), pushing deeper into the Universe (out to redshifts of z ~ 2) than previous non-focusing telescopes which were limited to the local Universe (z ≤ 0.1). We will perform a systematic study of the host galaxy properties (colours and morphologies) of AGN detected in the NuSTAR extragalactic survey program (shown on the sky in Figure 2). The host properties will be constrained using an extensive multiwavelength (optical and infrared) data set from ground- and space-based astronomical observatories. The results will be considered in the context of comparison samples, such as inactive galaxies and local AGN (such as those in the Swift BAT survey; Koss et al. 2011). This will allow us to test if, and when (cosmologically speaking), differences between the AGN-hosting and inactive galaxy populations materialise.

Nature of the project work

- The project is both observational and computational in nature. Tabular data from observational data sets will be accessed, manipulated, and cross-matched, to determine the properties of astrophysical objects (i.e., galaxies and AGN). There will also be opportunities to gain experience of directly analysing science data (e.g., images) from astronomical facilities (e.g., NuSTAR, the SDSS, Hubble space telescope).

- Application of typical research skills: use of software and/or programming, error analysis, simple statistical tests, and graphical representation of results.
References

Brandt & Alexander 2015, A&ARv, 23, 1, Cosmic X-ray surveys of distant active galaxies: The demographics, physics, and ecology of growing supermassive black holes
Kormendy & Ho 2013, ARA&A, 51, 511, Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies

Fig 1—Left: Optical image of a nearby AGN-hosting galaxy. In the optical light band, both the galaxy and the central AGN are luminous. Right: X-ray image of the same galaxy, matched in sky coordinates to the optical image. Only the central AGN is visible. From Brandt & Alexander 2015.

Fig 2: Diagram showing the distribution of NuSTAR extragalactic survey sources on the sky in the equatorial coordinate system. Out of the plane of the Milky Way (grey region), essentially all NuSTAR sources are AGN. From Lansbury et al. 2017.
17. High resolution spectroscopy of a hot Jupiter

Project summary:
The project involves inferring atmospheric signatures of an extrasolar hot Jupiter using very high resolution spectroscopy of the star-planet system in the near-infrared observed with a large ground-based telescope. The spectral signatures of the planet are deduced by detecting the doppler shift of the planetary spectrum relative to the stellar spectrum. This involves first accurately removing the systematics and telluric features from the combined spectrum and then cross-correlating the observed spectrum with model template spectra of the planet to infer the planetary signal.

Project description:
In recent years robust detection of molecules in exoplanetary atmospheres have been made using high-resolution doppler spectroscopy in the near infrared. This technique involves the detection of molecular lines in the planetary spectrum that are doppler shifted in wavelength due to the radial velocity of the planet (Snellen et al. 2010, Brogi et al. 2012, Birkby 2013). For close-in hot Jupiters, the orbital velocities are about 1 km/s whereas the stellar orbital velocities are significantly lower (e.g. below 100 m/s). Thus the spectrally shifted molecular lines of the planetary atmosphere are easily identifiable compared to those in the stellar spectrum as well as those in the telluric spectrum which is static. A template spectrum of a model planetary atmosphere that includes the sought after molecule is cross-correlated with the observed spectrum to detect the doppler shift in the molecular lines with phase thereby revealing the presence of the molecule. Critical to this method is the high resolution of the observed spectrum so that individual molecular lines can be resolved. Many of the successful observations in this area have been made using the CRIRES instrument on the Very Large Telescope (VLT) with a spectral resolving power of 100,000 in the near-infrared (Snellen et al. 2010). Moreover, since the planetary signal diminishes with the increased resolution the method has been successfully applied only to planets orbiting the brightest, i.e., nearby, stars. In the present project we will use this method to infer the atmospheric properties of a hot Jupiter using archival high resolution spectra of the system in the near infrared.

Background:
This method has been used to robustly detect CO and H$_2$O in several hot Jupiter atmospheres. The detections of these particular molecules are favored by the fact that they are expected to be the most dominant O and C bearing molecules in hot Jupiter atmospheres, especially for T $> \sim$1300 K, and they also have detectable absorption lines in the near-infrared where these atmospheres are most conducive to observe from ground. This wavelength range offers the optimal conditions because in the near-infrared the planet-star flux ratio increases with wavelength. Snellen et al. (2010) reported the first detection of CO using this technique in the hot Jupiter HD$\sim$209458b in transit which in turn also led to a constraint on the day-night wind velocity in the planetary atmosphere. Subsequent observations have led to the detection of CO and H$_2$O in the atmospheres of several transiting and non-transiting planets (e.g. Brogi et al. 2012, Rodler et al. 2012, Birkby et al. 2013).
Project details:
The project will involve constraining the atmospheric properties of a hot Jupiter exoplanet using archival spectra. This system has been previously observed with the CRIRES spectrograph on VLT at very high resolution ($R = 10^5$), spectra from which are publicly available and will be used in the present study. The project will involve data reduction of the raw spectra, followed by accurate detrending and removal of systematics, and finally using a high-resolution model grid to search for planetary spectral signatures in the data. The initial reduction of the raw data will be conducted using the existing CRIRES pipeline. The extracted spectra will then be analyzed using programs that will be built as part of the current project. This includes identification and removal of bad pixels, detrending, removal of telluric features, etc. The corrected spectra will then be cross-correlated against in house model template spectra to identify planetary signals in the data. More details on the method can be found in the references listed below (see e.g. Birkby et al. 2013).

Skills required:
The project will require adequate computing skills including some familiarity with data handling and numerical methods. Prior experience with astronomical spectroscopy is desirable. Proficiency in Python or IDL is desirable but any other programming language is also acceptable. Part-II level physics and astronomy will be sufficient for the project.

Relevant references:
Birkby et al. 2013, Messenger

General references:
Madhusudhan et al. 2016, Space Science Reviews, 205, 285
19. Measuring the sizes of ionized hydrogen near zones in high redshift quasars in the epoch of reionisation

**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 $z \sim 6.2$ quasars with H II near zone sizes $\leq 3$ proper Mpc that could indicate that these quasars may be young with ages $10^6$-$10^7$ years or lie in 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.

---

**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**
Courses needed are:

- Formation and Structure in the Universe

Useful references:


General references:


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

**Figure 1**: Optical spectrum of spectrum of a high redshift quasar showing redshifted hydrogen Lyman-α (λ_{rest}=121.6nm) emission and absorption signatures including near-zone region. Note the observed wavelengths of these UV transitions are observed in the red part of optical region. 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.
19. What is the optimal primary mirror shape for a space telescope?

| Supervisor I: Ian Parry, H57, email: irp@ast.cam.ac.uk |
| Supervisor II: Mike Irwin, APM1, email: mike@ast.cam.ac.uk |
| UTO: Ian Parry |

Introduction

For ground-based optical/NIR telescopes the most important feature of the primary mirror is its collecting area. The image quality it delivers via the quality of its construction is to some extent a secondary consideration because the Earth’s atmosphere blurs the images. The image quality of the telescope itself, which can be quantified by its point spread function (PSF), only has to be smaller than the PSF caused by the blurring due to atmospheric turbulence. For a perfect (i.e. diffraction limited) telescope the PSF has a FWHM of \(\sim \lambda/D\) where \(\lambda\) is the wavelength of the light and \(D\) is the width of the telescope’s primary mirror. The PSF caused by the atmosphere (the “seeing”) is typically \(\sim 1\) arcsec. So for telescopes with \(D>10\)cm and \(\lambda=500\)nm the diffraction limited PSF is better than the seeing. The biggest ground based telescopes have \(D \sim 8\)m and their image quality is totally dominated by atmospheric seeing.

The primary mirror of a ground based telescope is therefore invariably a filled circular aperture because for a given collecting area this minimizes the extent of the mirror. There’s no point in increasing \(D\) (for a given collecting area) to make \(\lambda/D\) smaller (to make the images sharper) because the spatial resolution is ultimately limited by the atmospheric seeing.

However, this is not the case for a space telescope. There is no atmospheric blurring so the \(\lambda/D\) PSF can be achieved. It is therefore possible to increase \(D\) (to minimize \(\lambda/D\)) for a given total mirror collecting area \(A = f \pi D^2/4\) where \(f\) is the fill-factor which is unity for a circular mirror and is \(< 1\) for other geometries.

The collecting area of a space telescope’s primary mirror is limited by the allowable launch mass. Various fill-factors and mirror geometries can in principle be implemented by an unfolding telescope structure. The aim of this project is to evaluate the telescope performance for a range of possible fill-factors and mirror geometries. Figure 1 shows a non-redundant aperture geometry which gives the spatial resolution of an 8m telescope but with a fill-factor of \(\sim 5\%\). In principle, such a geometry could give an 8m telescope in space with a mirror that is only 5\% the mass of a full circular 8m mirror.

Project Work

1. Devise figures of merit: There are 3 important quantities to consider, a) the collecting area, the FWHM of the core of the PSF and the background light adjacent to the central core of the
PSF (i.e. the limiting contrast). Different types of science require different things. For example, exo-planet transit spectroscopy needs collecting area but does not need good spatial resolution or high contrast capability whereas direct imaging spectroscopy of exo-planets needs all three. These figures of merit are essentially a way of providing a “score” for any telescope mirror geometry and will be based on a combination of the three parameters: area, resolution and contrast.

2. Model the PSF for various telescope mirror geometries and evaluate them using the figures of merit established in step 1). This modelling will be done using the PROPER IDL subroutine library. The student will write code in IDL to use these routines. Figure 2 shows an example.

3. Optimise the mirror geometry. This will involve understanding concepts such as non-redundant masks and Fourier-space coverage.

Figure 1: Example of a high spatial resolution aperture with a low fill-factor. The nine small circles form a non-redundant aperture with an extent of ~8m and a fill-factor of ~5%. Figure from Norris et al, 2014.

https://arxiv.org/abs/1405.7426,

Figure 2: Example of a mirror geometry (left hand image) and the PSF it produces (right hand image). The primary mirror is made of 8 mirror segments which are 5mx3.3m each with a total extent of D~24m. This geometry lends itself well to being unfolded from within an Ariane 6 rocket fairing. The PSF is shown using a logarithmic intensity scale.
20. Extreme matter accretion onto black holes in ultraluminous X-ray sources and active galactic nuclei

Supervisor I: Ciro Pinto (office H56, email cpinto@ast.cam.ac.uk)
Supervisor II: Andy Fabian (office H54, email acf@ast.cam.ac.uk)
UTO: Andy Fabian

BACKGROUND

In the centre of almost every galaxy there is a supermassive black hole (SMBH) weighing over million suns. The discovery of “fully grown” SMBH at high redshifts, when the Universe was young, challenges the theories of black holes growth, requiring long periods of high accretion, most likely above the Eddington limit. This is a focus of the next generation large missions, e.g. ESA’s ATHENA X-ray observatory, but cannot be investigated with the current instrumentation due to their large distances. Therefore, we need to study objects accreting at high rates in the nearby Universe.

Ultraluminous X-ray sources (ULXs) are extraordinary extragalactic, off-nucleus, point sources in galaxies and have X-ray luminosities above any known steady stellar process (> 3·10^{39} erg/s). They are powered by accretion onto compact objects such as neutron stars with strong magnetic fields and stellar mass black holes (BH) at or in excess of the classical Eddington limit. Therefore, ULXs provide the best workbench to study super-Eddington accretion and fast growth rates of black holes.

I recently published in *Nature* the discovery of X-ray emission and blueshifted (~0.2c) absorption lines in the high-resolution XMM-Newton spectra of the two archetypical ultraluminous X-ray sources NGC 1313 X-1 and NGC 5408 X-1. The absorption lines reveal the fastest, relativistic, outflow ever seen in a X-ray binary and is consistent with predictions by models of hyper-accreting stellar mass black holes. This discovery directly reveals the long sought, powerful winds in super-Eddington accreting sources and sheds new light on ULXs nature. This has opened up a new research field and I proposed an exciting follow-up project focusing on wind driving mechanisms. This awarded a huge amount of new observations being taken between summer and winter 2017.

![Figure 1: Artistic picture of an ultraluminous X-ray source. A compact objects, most likely a black hole, accretes matter from a companion star in the form of a disk (left). When accretion is high, radiation increases enormously and kicks a large amount of gas in the surrounding space. This gas forms a wind which absorbs the X-rays from the inner regions, leaving significant residuals to the best-fitting continuum models in ULX X-ray spectra (right).](image-url)
NATURE OF THE PROJECT

In a pioneer work we have found evidence for an anti-correlation between the strength of the wind and the spectral hardnes of ULX NGC 1313 X-1; this suggested that the wind is strong when the source is “soft”, i.e. when we can directly see the accretion disk (Figure 2, left). I propose to search for wind features in both medium- and high-resolution X-ray spectra of the brightest ULXs and test the connection between the strength of the wind features and the ULX spectral state. This will either provide further evidence into this scenario or probe new physics in case we find surprising mismatches. This work will made use of XMM-Newton and Chandra observations including two newly awarded large (750+500 ks) programs.

Alternatively, the same techniques can be used on very bright X-ray spectra of narrow line Seyfert 1 (NLS1) active galactic nuclei which are also thought to be accreting above the Eddington limit. NLS1 also show strong outflows carrying a lot of energy and affecting the stellar evolution in the host galaxies through the process known as Feedback. I have produced a sample of 20 powerful sources to be looked at. A line-scan in high-resolution X-ray spectra will allow the detection of fast winds outflowing at high fractions of the light speed. The ratio between the wind kinetic power and the bolometric luminosity of the AGN will estimate the efficiency of Feedback.

This work will use the advanced UV / X-ray spectral fitting package SPEX which is optimal for plasmas in extreme conditions and is very easy to learn as well as the reduction software for Chandra (CIAO) and XMM-Newton (XMM-SAS) data. The archives of the X-ray satellites have extraordinary, high quality, data that will be quickly reduced providing well-exposed spectra. SPEX enables an advanced modelling of the spectra to measured the velocities and other characteristics of the winds as well as other important properties of the ultraluminous X-ray sources.

USEFUL REFERENCES


Figure 2: Cartoon of a physical model of high mass accretion rate sources. The light blue region shows the soft X-ray emission of the accretion disk, altered by a photosphere of a radiatively-driven optically-thick wind. The dark blue region, closer to the compact object is dominated by highly variable, optically-thin, turbulent Comptonization emitting high-energy (>1 keV) X-rays (left). XMM-Newton high-resolution spectrum of the ULX NGC 1313 X-1 with overlaid a model of thermal collisionally-ionized emission (T~10^7 K) and a relativistically (v~0.2c) blueshifted photoionized absorption. The dotted lines indicate the blueshift from the rest-frame transitions (right).
21. The fight between cooling and heating in clusters of galaxies

Supervisor I: Ciro Pinto (office H56, email: cpinto@ast.cam.ac.uk)
UTO: Andy Fabian (office H54, email: acf@ast.cam.ac.uk)

BACKGROUND

Clusters of galaxies are the largest gravitationally-bound individual objects in the Universe. The vast majority of their baryonic mass is found in the form of hot $10^6$ K gas, known as the intra-cluster medium (ICM). The density of this gas strongly increases in the cores of the galaxies where the radiative cooling time is less than 1 Gyr. Theoretical models predict large mass deposition of up to 100s of solar masses per year in the cores of these objects. Such high values are not detected; in particular there is a significant lack of cool gas below 5 million K, presumably due to heat produced by energy released in galaxy mergers, sloshing of gas within the gravitational field or by the powerful jets generated by matter accreting on the supermassive ($10^6$ M$_\odot$) black holes host in the centres of the galaxies. It is still under debate which of these scenarios is most feasible and I propose to use advanced X-ray spectroscopy techniques to investigate the nature of clusters heating.

![Figure 1: Chandra X-ray image of the Perseus intra-cluster medium with low-pressure expanding regions, in purple, filled with relativistic particles from the outbursts of the central supermassive black hole (left). These jets release enormous amounts of energy which inflate cavities/bubbles and heat the gas, possibly preventing cooling flows (centre). Centaurus cluster of galaxies with gas sloshing in the dark matter gravitational potential (right).](image)

Our recent discovery of the long sought cool (~ 2 mln K) gas in a sample of giant ellipticals in clusters of galaxies opened up a new window to study their thermodynamics. This was revealed by the detection of O vii emission lines in their high-resolution XMM-Newton spectra (see Figure 2). The comparison of the amount of gas at $10^{5.5}$ K (O vii), $10^{6.3}$ K (O viii) and $10^{6.7}$ K (Fe xvii) may reveal the nature of the O vii phase and cooling – heating balance in these massive astronomical objects. Turbulence is thought to transfer heating throughout the ICM. It can be produced by jets from the active galactic nuclei (AGN feedback), galactic mergers and gas sloshing in the dark matter potential. It can be measured through the widths of the X-ray emission lines and from ratio between turbulence-dependent and turbulence-independent emission lines. Therefore, turbulence estimates are crucial to understand the thermodynamical status of the intra-cluster medium and are among the main focuses of the current and next generation X-ray large missions (e.g. XARM, ATHENA).
USEFUL of enables extraordinary, Chandra plasmas This and (affected theoretical work) takes place. This project will be done with archival and new observations, including a newly awarded XMM-Newton observation of NGC 1404, a giant elliptical galaxy falling into the Fornax cluster of galaxies (Figure 2).

This work compares theoretical predictions and observations pleasing students interested to either theoretical aspects of astrophysics or observational techniques. As a by-product, we could develop a theoretical model to determine the turbulence from the ratio between resonance optically-thick lines (affected by turbulence) and optically-thin lines (insensitive to turbulence). This can be done in IDL and C/bash-shell, which are my programming languages or any other preferred by the student.

This work will use the advanced UV / X-ray spectral fitting package SPEX which is optimal for plasmas in extreme conditions and is very easy to learn as well as the reduction software for Chandra (CIAO) and XMM-Newton (XMM-SAS) data. The archives of the X-ray satellites have extraordinary, high quality, data that will be quickly reduced providing well-exposed spectra. SPEX enables an advanced modelling of the spectra to measure mass deposition rates, metal abundances, turbulence, temperature structure and other important properties necessary to understand the nature of the heating phenomena occurring in the galaxies.

USEFUL REFERENCES

- A review on heating of galaxies with AGN http://arxiv.org/abs/1204.4114
- A review on X-ray spectroscopy of galaxy clusters http://arxiv.org/abs/0907.4277
- My first paper on O VII discovery in ellipticals http://arxiv.org/abs/1411.0709
- My follow-up papers on O VII studies in ellipticals http://arxiv.org/abs/1606.04954
  and turbulence constraints in ellipticals, groups and clusters of galaxies http://arxiv.org/abs/1501.01069

Figure 2: XMM-Newton X-ray spectrum of NGC 1316 with strong O vii lines (left). Map of the Fornax cluster: NGC 1404 is in collision with its core (NGC 1399) undergoing sharp shocked-edges and gas stripping (right).

NATURE OF THE PROJECT

I propose to constrain the turbulence and the amount of cool O vii gas in a sample of about 10 giant elliptical galaxies. They will be compared with the presence of AGN jets, galactic mergers and sloshing in order to unveil the main heating source and to address where/how cooling – heating balance takes place. This project will be done with archival and new observations, including a newly awarded XMM-Newton observation of NGC 1404, a giant elliptical galaxy falling into the Fornax cluster of galaxies (Figure 2).
22. Seeing the Cosmic Web in Lyman-α Emission

Advisors: Ewald Puchwein (K20; puchwein@ast.cam.ac.uk) Girish Kulkarni (K16; kulkarni@ast.cam.ac.uk) Martin Haehnelt (UTO; K27; haehnelt@ast.cam.ac.uk)

The cosmic web, as seen in observations of light emitted by stars in millions of galaxies (left panel), and as predicted by theory using a cosmological simulation (right panel). In this project, we will use simulations to ask if the cosmic web could be seen in Lyman-α light emitted by the hydrogen in it, instead of star-light from galaxies. This may lead to a new way of measuring the Universe.

Over the last few decades, astronomical surveys have measured three-dimensional positions of millions of galaxies, and have revealed that structure in the Universe forms a cosmic web in which galaxies are preferentially located in a tary pattern (left panel of the f This is in agreement with theoretical predictions (such as that shown in the right panel of the f Therefore, measurements of the cosmic web enable us to accurately infer properties of the Universe, such as its density and age. However, most of the matter in the Universe is not located in galaxies; it is distributed in the intergalactic medium (IGM) that the space between them. Thus, surveys that only observe galaxies, by detecting light emitted by the stars contained in them, miss most of the matter in the Universe. Would it be possible to design a survey that directly detects the intergalactic gas itself? In this project, we will address this question by asking how bright the intergalactic gas is in theoretical models of the IGM. We will focus on the brightness of light with a wavelength of 1,216 Å, corresponding to the Lyman-α spectral line of a hydrogen atom, because
most of the intergalactic gas is hydrogen and emission is usually the brightest at this wavelength.

Measuring the cosmic web in Lyman-\(\alpha\) emission would also be an important step forward in completing the census of the matter content of the Universe, leading to a fuller understanding of the IGM itself. So far the intergalactic gas has been mostly observed in Lyman-\(\alpha\) absorption, seen as a forest of dark absorption lines in the spectra of bright distant objects such as quasars. The downside of this method is that it restricts us to a one-dimensional view of the intergalactic medium along lines of sight towards these quasars. Observing the cosmic web in Lyman-\(\alpha\) emission will help overcome this limitation by uncovering the IGM in full three-dimensional glory.

**Project Outline**

Intergalactic gas emits Lyman-\(\alpha\) photons via two processes: (a) recombinations of free electrons and protons, and (b) collisional excitation of hydrogen atoms. In this project, we will investigate these two processes using cosmological simulations from the Sherwood Simulation Suite (nottingham.ac.uk/astronomy/sherwood), which includes some of the most sophisticated cosmological simulations performed so far. The high dynamic range of these simulations allows more realistic modelling of the IGM than was possible before. The project will involve the following steps:

1. Calculate recombination and collisional excitation rates  
2. Derive the implied Lyman-\(\alpha\) emission from intergalactic gas  
3. Compare predicted brightness to experimental sensitivities

An interest in high-performance computing and some experience in computer programming would be valuable. Some code for this analysis is already available.

**Bibliography**

- See Meiksin (2009, Rev. Mod. Phys., 81 1405) for a review of what we know about the intergalactic medium.  
- Results from an attempt to observationally detect the Lyman-\(\alpha\) emission from the intergalactic medium, using the VLT telescope in Chile, are presented by Gallego et al. (2017, arXiv:1706.03785 [astro-ph.CO]).
23. Ultra-fast outflows from tidal disruptions of stars by massive black holes

Supervisor I: Christopher Reynolds, H15, email: csr12@cam.ac.uk
Supervisor II: Ciro Pinto, H56, email: cpinto@ast.cam.ac.uk
UTO: Christopher Reynolds

Project summary:
The disruption and subsequent accretion of a star by a supermassive black hole (SMBH) at the centre of a galaxy gives us an important window into the physics of black hole accretion. SWIFT J1644+57 is a remarkable example of one of these tidal disruption events (TDEs) – it achieved an extremely high luminosity and launched a relativistic jet that defies many theoretical models. While this event occurred in 2011, a recent re-analysis of X-ray data found signatures of a massive ultra-fast outflow with speeds >100,000km/s. In this project, we will use computer (Monte Carlo) simulations to model and understand these X-ray signatures thereby allowing us to understand the structure of the accretion flow in this source. When completed, these models will be a valuable tool for understanding future extreme TDEs, deepening our understanding of these extreme sources.

Project description:

When a star orbits too close to its galaxy’s supermassive black hole (SMBH), it can be ripped apart by the tidal forces of the black hole. Some of the stellar debris then accretes onto the SMBH, forming a transient accretion disk that eventually drains into the SMBH on timescales of months to years. TDEs may provide a valuable laboratory for studying black hole accretion in detail since we can watch and study them as they pass through a huge range of mass accretion rates (and hence luminosities). While TDEs were first predicted in the 1980s (Rees 1988), it is only in the past few years that we have been routinely and robustly detecting them and realizing their promise as test-beds for accretion disk theory.

SWIFT J1644+57 is a TDE first discovered in the hard X-ray band by NASA’s Swift satellite in 2011 (Burrows et al. 2011). Subsequent observations found that it was remarkably luminous, so much so that radiation forces are expected to drive powerful outflows (i.e. the source vastly exceeds its Eddington limit). It was also discovered to possess a relativistic jet (Zauderer et al. 2011), likely directed almost at us, with a power that challenged our standard models for the production of jets in black hole accretion disks (e.g. see Introduction of Tchekhovskoy et al. 2014).

A recent and careful re-analysis of X-ray data from the XMM-Newton and Suzaku satellite by Kara et al. (2016) found X-ray signatures of a massive ultra-fast outflow with a velocity of 0.3—0.5c (100,000—150,000km/s). Specifically, they found a blue-shifted emission line of highly-ionized iron thought to be excited by irradiation of the outflow by the central powerful X-ray. By applying Fourier-based analysis techniques, they also discovered time-lags corresponding to the “echo delay” of the iron line as compared with the central X-ray source. This exciting discovery opens up the possibility of mapping the geometry and flow speeds of this luminous accreting SMBH (Kara et al. 2016; Lu et al. 2017). However, the models required to conduct such a study are still lacking.

Project details:
We wish to build a model that can describe both the X-ray spectral and the timing/echo signal for a luminous source with a geometry appropriate for SWIFT J1644+57. Unlike less-luminous accretion disks, we believe that radiation forces make these luminous accretion disks very puffy, with a geometry that is better describes as torus-like rather than disk-like. The relativistic jet and
the ultra-fast outflow will then flow up through the central funnel (or eye-wall) of the accretion flow (see Figure). Starting from this geometry, we shall conduct Monte Carlo (MC) simulations of X-ray photons as they propagate through the system and interact with matter, eventually making it out to be observed by our telescopes. The MC simulations will be tested and validated against analytic solutions, possible in certain restricted cases. We shall then examine more realistic cases, computing both the X-ray spectrum and the time-delay signals as a function of parameters of the model, phrasing the latter in the terms measured by the observers (i.e. in the Fourier-domain).

Once the MC simulations are complete, we will then apply our model to the XMM-Newton and Suzaku data from SWIFTJ1644+57 thereby obtaining the best constraints to date for the structure of the accretion disk and outflows. More importantly, these models will become part of the tool-kit that TDE researchers use to study other/future TDEs that are found to possess these signals.

**Proposed geometry for central accretion flow in a luminous TDE such as SWIFTJ1644+57.** The accretion disk is inflated by radiation-pressure, better being described as an accretion torus. A jet is launched along the funnel, although controversy remains about its driving physics. The walls of the funnel are accelerated by the tremendous radiation pressures and may explain the observed ultra-fast outflow. *Figure from Kara et al. (2016).*

**Skills required:**
Experience with a compiled computer language such as C, C++, or Fortran. Working knowledge of Special Relativity and Fourier transforms.

**Useful references:**
General references:
24. Grain growth in proto-planetary discs in binary systems

Supervisors: Giovanni Rosotti, H21; email: rosottii@ast.cam.ac.uk
Cathie Clarke (UTO), H10; email: cclarke@ast.cam.ac.uk

Background

Planets form in discs composed of dust and gas in rotation around young stars. In these discs, small grains of dust grow from sub-micron size to become planetesimals, asteroids, planetary cores and ultimately planets, a range of more than 10 orders of magnitude in size!

These growth processes are far from understood. Several theoretical “barriers” have been identified that impede the grain growth, yet we know that ultimately nature forms planets with high efficiency. In the current understanding, grains “drift”, i.e. spiral towards the star due to the aerodynamic interaction with the gas, with a velocity that increases for larger grains. For typical grain sizes of ~1mm, the drift timescale is shorter than the lifetime of discs. To explain the fact that we still see dust in these discs, a large reservoir of grains at large radii is needed, still in the process of growing and therefore not drifting. Eventually, once this reservoir is depleted, the disc becomes dust free.

A possible, little explored way to test if this picture is correct is to use binaries. Discs around one of the two stars of a binary are subject to the same processes as around single stars, with one important difference: the gravitational effect of the companion. This interaction truncates the outer parts of the disc, setting an upper limit on the disc size which depends on the binary separation. Binaries therefore can be regarded as a controlled experiment set up by nature, in which one parameter (the disc outer radius) is held fixed. This is likely to affect for how long these discs can retain their dust. In addition, a large fraction of stars are in binaries, and many have planets; understanding planet formation in binaries is certainly important on its own.

Nature of the project

This is a theoretical project that requires running simple numerical simulations with an existing code written by the supervisor. Running and analyzing the simulations will require the student to gain familiarity with a scripting language, preferably Python and to run simulations on a Unix-based system.

The project will consist mainly in running simulations of the evolution of discs in binary systems, including the processes necessary to describe the growth and drift of the dust. In a first phase the focus will be on understanding how long discs in binary systems can retain dust, as a function of the main parameters of the system (binary separation, disc viscosity, …).

In a second phase, the focus will shift to understanding if the model predicts different resulting grain sizes distributions compared to single stars. This has observational implications because it is now possible, thanks to new telescopes such as ALMA, to measure the grain sizes in discs and how they vary with radius.

The last phase of the project will consist in making observational predictions for measurements of grain sizes in discs in binaries.
References

Articles can be found online by searching for author and year at http://adsabs.harvard.edu/abstract_service.html or by following the link.

- For an investigation of the evolution of a disc in a binary system (of the gas only), see Armitage, Clarke & Tout (1999), MNRAS, 304, 425, http://adsabs.harvard.edu/abs/1999MNRAS.304..425A
Figure 1: ALMA observations of proto-planetary discs in binary systems. From Akeson & Jensen (2014).

Figure 2: The evolution of the dust surface density, as a function of the disc radius and grain size, in a disc around a single star. From Birnstiel, Klahr & Ercolano (2012)
25. Detecting the signatures of planet formation around low mass stars

Supervisors: Giovanni Rosotti, H21; email: rosotti@ast.cam.ac.uk
Attila Juhasz, H22, email: juhasz@ast.cam.ac.uk
Cathie Clarke (UTO), H10; email: cclarke@ast.cam.ac.uk

Background

After the first exoplanet was found in 1995, we have learnt a great deal about exoplanetary systems. But most of the amazing discoveries made so far have targeted solar mass stars. While these stars are similar to our own, they do not comprise the majority of stars in the galaxy. A major breakthrough came recently with the discovery of the planetary system around the star TRAPPIST1, which has a mass of only one tenth of the Sun. This system is comprised of 7 earth-like planets, 3 of which in the habitable zone.

Many studies are now looking for planets around common, low mass stars. However, they still consider stars on the main sequence, which are Gyr old. During this time, planetary systems have evolved significantly. Therefore, to understand planet formation, we need to look at planetary systems when they are young.

Young stars are surrounded by discs of dust and gas where planets form. While these discs prevent us from using the transit technique to detect planets, we can still use them to our advantage. Young forming planets, if they are massive enough, create observable structures in discs due to their gravity in the form of annular gaps in density structure of the disc. Thanks to the most expensive ground-based telescope ever built, the Atacama Large Millimetre Array (ALMA), we can now see these gaps and infer the presence of planets in discs.

Project outline

The project will consist in generating ALMA simulated observations of discs around low mass stars with planets. The goal of the project is to assess under which conditions (e.g. planet mass and distance from the star) the structures created by the planets are detectable. For solar mass stars, the limit is roughly 12 Earth masses if the planet orbits 30 astronomical units away from the star. The ability of opening a gap depends mostly on the mass ratio between the disc and the planet; a star with a mass of a tenth of the Sun should therefore allow us to go down to the Earth mass regime!

However, the disc is a fluid structure and an important quantity that determines how easy it is for a planet to carve a gap is its temperature. The first step of the project will be to compute the temperature of discs around low mass stars using the radiative transfer code RADMC3D.

Armed with this knowledge, we will select the right temperature to use from a library of previous hydro-dynamical simulations of planet-disc interaction that the supervisor has run. Exceptionally good students might also run directly the hydro-dynamical simulations. With this step we will compute the minimum planet mass that is physically required to create a structure in these discs.

The last step of the project will involve generating mock observations using the code CASA, that mimics the instrumental effects of ALMA, most importantly the spatial resolution and the limited signal to noise of the observations. These instrumental effects might prevent us from detecting structures even if they are physically present; discs around low mass stars in particular are known to be relatively faint and the noise in the data might be the major show-stopper to detect gaps. This
step will allow us to assess the minimum planet mass that is observationally required to create a structure in these discs.

This project will require the student to gain familiarity with a scripting language, preferably Python, and to run simulations on a Unix-based system.

References

Articles can be found online by searching for author and year at http://adsabs.harvard.edu/abstract_service.html or by following the link.

• For the article about TRAPPIST 1, see Gillon et al, Nature, 542, 7642, http://adsabs.harvard.edu/abs/2017Natur.542..456G

Figure 1: ALMA observations of the discs around the stars HL Tau (left) and Tw Hya (right). The dark rings in the images are probably the signposts of planets.
26. The gravitational sphere of influence of the black hole at the centre of NGC4472

Supervisors: Helen Russell, Office: H54, Email: hrr27@ast.cam.ac.uk
Andy Fabian, Office: H54, Email: acf@ast.cam.ac.uk
UTO: Andy Fabian

Background

The supermassive black hole (SMBH) located at the centre of most galaxies is now understood to play a significant role in the evolution of its host. Gas accretion onto the black hole powers radiation, winds and relativistic jets that heat the surrounding gas in the host galaxy in a process known as AGN (active galactic nucleus) feedback. This energy input suppresses gas cooling and star formation and limits the growth of massive galaxies at late times in the Universe.

Observations of active radio galaxies in the nearby Virgo cluster provide the most detailed view of the complex interactions between the central black hole and the surrounding hot gas. Figures 1 and 2 show Chandra X-ray observations of the hot gas within two Virgo galaxies - M87 and M84. On large scales, the radio jets launched by the central black holes have displaced the hot gas to produce a series of cavities in the X-ray image. On smaller scales, the hot gas will be accreted if it falls within the supermassive black hole’s gravitational sphere of influence, where the gravitational potential of the black hole overwhelms the thermal gas motions. This region can only be resolved by Chandra in a handful of nearby galaxies, including NGC4472, which is the subject of this project.

The main aim of this project is to map the gas density and temperature structure at the gravitational sphere of influence of the central black hole to study interactions between the recent jet outburst and the gravitationally captured hot gas. We will search for a temperature increase due to the black hole’s gravitational influence and determine whether rapidly cooling hot gas is fuelling the AGN activity.

Nature of the project work

This is primarily an observational project using archival Chandra X-ray data of NGC4472 to study the hot gas properties within the SMBH’s gravitational sphere of influence. The standard X-ray analysis software packages ciao and xspec will be used to reduce the data and produce maps of the gas temperature, density and metallicity. A possible plan for the project work is as follows.

- Analyse Chandra data to produce images and study the cavity structures generated by the radio jets
- Map the gas temperature, density and metallicity on large scales and within the black hole’s gravitational sphere of influence
- Determine the density and temperature gradient within the gravitational sphere of influence and compare this with model predictions
- Calculate the accretion rate from the multi-temperature hot gas and determine if this is sufficient to power the jet activity
Figure 1: Left: Chandra X-ray image of hot gas in the Virgo elliptical galaxy M84 with an inset image showing the X-ray (blue) and radio emission (red) from Finoguenov et al. (2008) and Laing & Bridle (1987). The AGN is located at the X-ray peak. Radio jets launched by the black hole have displaced the surrounding hot gas to create a series of cavities with bright rims. The gravitational sphere of influence extends to roughly an arcsec from the AGN and is resolved by Chandra.

Figure 2: Left: Chandra X-ray image of the hot gas and jet in the Virgo elliptical galaxy M87. Accretion onto the central black hole is powering a jet, which is inflating large radio bubbles into the surrounding hot gas. The cavities in the X-ray image show where hot gas has been displaced by radio plasma. The AGN is so bright that the X-ray observation is piled up, which produces image artifacts such as the hole at the centre and the readout streak. The black hole’s sphere of influence is marked by the outer dashed circle.

Useful texts

- For an introduction to the properties of galaxy clusters see the textbook by Craig Sarazin ‘X-ray Emission from Clusters of Galaxies’. Also available online at http://ned.ipac.caltech.edu/level5/March02/Sarazin/frames.html

- For a review of AGN feedback see Fabian et al. (2012, ARA&A, 50, 455).

- For a detailed study of M87 and some of the analysis involved in this project see Russell et al. (2015, MNRAS, 451, 588) and references therein.
27. **Dynamical models of globular clusters**

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

**Project summary** The aim of this project is to develop a suite of flattened, rotating action-based dynamical models of globular clusters based on the King model.

**Project description** The King model is a simple dynamical model for a tidally-truncated spherically-symmetric isotropic non-rotating globular cluster (see Fig. 1). The student will develop an action-based distribution function that is a good approximation to the King model and use this model as a base to develop flattened and rotating globular cluster models. Time permitting, these models will be fitted to photometric and spectroscopic globular cluster data to measure the degree of rotation in globular clusters and its relation to flattening.

**Background** Globular clusters are collision-dominated systems which evolve through a series of collisionless equilibria via the Fokker-Planck equation. Therefore, for fitting globular cluster data we require flexible dynamical equilibria which are simultaneous solutions of the collisionless Boltzmann equation and Poisson’s equation as the visible matter provides all the gravity. By Jean’s theorem, the collisionless Boltzmann equation is satisfied by expressing the distribution function (df) in terms of the action variables. Self-consistency is ensured by iteratively relaxing the proposed distribution function [Binney, 2014]. The action variables \( \mathbf{J} \) are dynamical invariants which are constant along an orbit in the potential \( \Phi \). There are three actions \( (J_R, J_\phi, J_z) \) that describe the extent of the orbit in each dimension (radial, azimuthal and vertical). For instance, in a spherical potential, two of the actions are given by components of the angular momentum.

**Project details** The construction of action-based dfs that approximately reproduce double-power-law density profiles with variable anisotropy is well understood [Posti et al., 2015; Williams & Evans, 2015]. Jeffreson et al. [2017] demonstrate how to construct an action-based modified Plummer df that approximately reproduces the density profiles of globular clusters (see Fig. 2). However, King models do a significantly better job of reproducing the density profiles of observed globular clusters, which are tidally truncated at radius \( r_1 \). The King model \( f_K \) is an isotropic truncated distribution function described by

\[
f_K(E) = \begin{cases} 
\rho_1 (2\pi \sigma^2)^{-3/2} (e^{E/\sigma^2} - 1) & E > 0, \\
0 & E \leq 0,
\end{cases}
\]

where \( E = \Phi_0 - E \) with the energy \( E \) and \( \Phi_0 \) is the potential at the boundary \( r_1 \). To convert this df into an action-based df, the student will numerically find the actions as a function of energy which may be inverted to find the Hamiltonian as a function of the actions \( H(\mathbf{J}) \) and hence \( f_K(H(\mathbf{J})) \). The goal would be to find an approximate analytic form for this df by proposing fitting functions that reproduce the numerical result e.g.

\[
f_K(\mathbf{J}) \propto e^{L y(1+L^a)(8-\gamma)/\sigma} - 1 .
\]

where \( L = (J_R + D(\mathbf{J})J_\phi)/J_0 \) and \( J_0 \approx \sigma r_0 \). One route towards construction of appropriate fitting forms will be to investigate the limiting behaviour of high and low energy radial and tangential orbits [e.g. Williams & Evans, 2015]. If this methodology proves successful, it may be possible to extend the approach to reproduce other lowered isothermal models such as the Wilson or Woolley models.

With an appropriate action-based df that reproduces the King profile, the student will flatten the model by scaling the vertical action part of the df \( J_z \rightarrow J_z/q_z \), relax the models to self-consistency and inspecting the model properties. Additionally, rotation may be included by adding on dfs which are odd in the angular momentum. Given sufficient time, the student will investigate the success with which these models reproduce the surface density profiles from photometric data and line of sight...
mean velocity and velocity dispersion profiles from spectroscopic data. Such an approach would follow the work of Jeffreson et al. [2017] who analysed a sample of globular clusters using double-power-law action-based distribution functions.

![Figure 1: 3d (a) and 2d (b) profiles for four King models of different concentration (taken from Binney and Tremaine (2008) Fig. 4.8).](image1)

![Figure 2: Numerical $f(J)$ with simple fit for modified Plummer df (top) and corresponding density profiles (bottom) with varying anisotropy.](image2)

**Skills required** The student should have a good knowledge of Lagrangian and Hamiltonian dynamics. In addition, the student should be familiar with both C++ and Python.

**Useful References**


**General References**

28. The shapes of globular clusters from Hubble photometry

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

Project summary The aim of this project is to measure the surface density profiles of globular clusters using Hubble photometry, in particular focussing on the shapes of the isophotes and their variation with distance from the cluster centre.

Project description The Hubble Space Telescope UV Legacy Survey of Galactic Globular Clusters [Soto et al., 2017, see Fig. 1] and the ACS Survey of Galactic Globular Clusters have produced five-band homogeneous photometry of 57 globular clusters in our Galaxy. The goal of the project is to model the shapes of the globular clusters by fitting parametrised models to extinction- and completeness-corrected point source catalogues.

Background The shapes of globular clusters are related to their formation mechanism, tidal interaction, degree of rotation or all of the above. The formation and evolution of globular clusters remains a mystery with recent photometric and spectroscopic observational evidence revealing a diversity of stellar populations. Several studies have investigated the dynamical signatures of different formation scenarios for multiple populations [Henault-Brunet et al., 2015; Mastrobuono-Battisti & Perets, 2016] and demonstrated that early time dynamical differences (e.g. flattening and rotation) persist to the present time. Accurate measurements of the ellipticity may distinguish different formation scenarios.

There are two sources for ellipticities of globular clusters. The first is the work of White & Shawl [White & Shawl, 1987] who, using photographic plates, provide estimates of the isophotal ellipticity near the scale radius. The second is from Chen & Chen [2010] who use the 2MASS point-source catalogue to measure the ellipticity at larger distances from the globular cluster centres. In general, the results from these two works disagree which may be attributed to genuine evolution of the ellipticity with radius or observational issues (e.g. differential reddening). There is a need for characterisation of the ellipticity profiles of globular clusters (see Fig. 2 for the ellipticity profile of 47 Tuc).

Project details For each globular cluster, the student will begin by correcting the source catalogues for extinction and assessing the degree of completeness. The student will then form extinction-corrected magnitude-limited catalogues for each cluster. From a set of measured stellar on-sky positions $D = \{x_i, y_i\}$, the probability of a set of parameters $P$ that describe the surface density profile $\Sigma(x, y|D)$ is given by Bayes Theorem as

$$p(P|D) \propto p(P) \prod_i \Sigma(x_i, y_i|P)$$

such that best-fitting parameters can be found by maximising $p(P|D)$ with the uncertainties estimated using Markov Chain Monte Carlo (MCMC) methods. The student will learn how to implement probabilistic models and sample from these using a number of modern probabilistic software packages (emcee, Multinest, STAN).

The surface density profile will be fitted using a mixture model which accounts for a constant background contamination: $\Sigma(x, y|P) = \Sigma_m(x, y) + n_b$. The functional form for the model surface density $\Sigma_m$ is given by

$$\Sigma_m(x, y) = \Sigma_m(m(x, y))$$ where $m^2(x, y) = \frac{1}{(1 - E)} (x\cos \theta - y \sin \theta)^2 + (x\sin \theta + y \cos \theta)^2$, 

such that the surface density is stratified on concentric ellipses with the choice of $\Sigma_m(m)$ controlling the radial profile. Initially, the fitting will use a Plummer model and a fixed ellipticity $E$ and position angle $\theta$. More complex models will be developed that allow for variation in the ellipticity ($E(m)$) with distance from the cluster centre as well as isophote twisting ($\theta(m)$) using e.g. linear or quadratic models. Additionally, the simple two-parameter Plummer model can be replaced with the three-parameter King model that reproduces the tidal truncation observed in many globular clusters [Binney & Tremaine,
The degree to which the more complex models better fit the data will be evaluated using the Bayesian evidence ratio computed with Multinest.

Figure 1: Trichromatic stack image of NGC 6681 (from Soto et al. 2017).

Figure 2: Ellipticity profile of 47 Tucanae: dashed line shows the ellipticity measurement from White & Shawl [1987] and the solid line from Chen & Chen [2010] (from Bianchini et al. 2013).

With a satisfactory set of model fits, the student will conclude the project by assessing whether the shape profiles of the globular clusters are correlated with any other globular cluster properties (both internal and orbital properties). Additionally, time permitting, the student can measure whether there is a preferential alignment of the major axes of the globular clusters with respect to the Galactic centre.

Skills required The student should be familiar with statistics and have some knowledge on the properties and structure of globular clusters. The project will involve writing and running probabilistic models for which some knowledge of Python would be good (although other programming languages could be used).

Useful References


General References

29. Volcanism on hot super-Earths: how and why?

Supervisor I: Oliver Shorttle (H20, os258@ast.cam.ac.uk)
Supervisor II: Nikku Madhusudhan (H18, email: nmadhu@ast.cam.ac.uk)
UTO: Oliver Shorttle

Project summary:
Spectra of rocky exoplanets allow constraints on their atmospheric properties which, in turn, could provide insights into their geological conditions. One first-order interaction a rocky planet can have with its atmosphere is through volcanic eruptions, which on both long and short timescales modify atmospheric chemistry and opacity. This project will consider the physics of two modes of volcanic activity and how appropriate they are for describing volcanism on super-Earths and thus explaining the enigmatic time dependence that has been observed on the super-Earth exoplanet 55 Cnc e.

Project description:
We are approaching an era in which astronomical observations may detect the long-term and time-dependent signatures of volcanism in planetary atmospheres through their spectra. Magma production and volcanism are basic characteristics of geologically active planets and are essential in abiotic chemical cycling. Identifying the presence of volcanism in extrasolar planetary atmospheres will therefore provide fundamental insight into the state of rocky extrasolar planets, and is the beginning of their geophysical characterisation. One promising candidate planet for volcanism is 55 Cancri e, where time-dependent variations in the thermal emission have been interpreted as resulting from extensive volcanic activity (Demory et al. 2016). However, 55 Cancri e is nearly 8 Earth masses and experiences dayside temperatures in excess of 2000 K. This project will extend existing volcanic models to operate in these extreme regimes of short-period super-Earths, and so provide the framework for detection and interpretation of their temporal variability.

Background:
Volcanism on Earth is driven by convection in the planet’s interior, as rock decompresses towards the surface it partially melts and the melt is extruded towards the surface to ultimately form volcanoes. The presence of volatile elements dissolved in the magma, such as water, drives explosive fragmentation of the magma as it erupts, producing the classic large eruption columns that can extend tens of kilometres into the stratosphere. On hot extrasolar planets, the scenario that drives large-scale volcanic perturbation of the atmosphere must be quite different. Firstly, as atmospheric pressure increases, the degree of volatile exsolution from magma decreases, this removes the driving force for explosive volcanic activity in planets with massive atmospheres. Secondly, planets with high equilibrium temperatures may have had their interiors desiccated by the pervasive melting of the planet’s surface. Combined, these factors suggest that Earth-like volcanism may be rare on planets such as 55 Cnc e and its ability to perturb atmospheric opacity limited. This project will provide important constraints on the efficacy of these classical volcanic models, and explore alternative modes of volcanism relevant to hot super-Earths.

Project details:
The student will develop models for two modes of volcanic activity 1) ballistic volcanism (see Wilson & Keil 2012) and 2) volcanic plume volcanism (see Woods & Bower 1995). Each of these
models provides semi-analytic solutions to the physics of a volcanic eruption, motivated by study of solar system bodies. The dependence of volcanic perturbation to astrophysical observables will be explored as a function of planet mass and atmospheric structure. The models will be applied to 55 Cnc e to understand its time dependent thermal emission. Shortcomings of the models will be discussed, and modifications of the physics considered in light of 55 Cnc e’s likely molten surface.

**Skills required:**
Basic physics at part-I level is required along with some background in basic fluid dynamics. Experience of computational work is expected as the project will involve solving coupled differential equations numerically.

**Useful references:**

**General references:**
30. Sublimating exoplanetary material around white dwarfs

Supervisor: Rik van Lieshout (H23, lieshout@ast.cam.ac.uk)
UTO: Mark Wyat (H37, wyatt@ast.cam.ac.uk)

Project summary:
Planetary systems are known to exist around stars of virtually all stages of their evolution. For white dwarf stars, the presence of planets is inferred from the metal pollution seen in the stellar atmosphere. This pollution is caused by planetary material (e.g., bodies like asteroids or comets) that has migrated inward from the remnant planetary system and has been accreted onto the star. During this process, larger bodies that pass close to the white dwarf are disrupted by the large tidal forces, creating clouds of debris orbiting the star. Indeed, some white dwarfs show evidence of compact circumstellar debris discs in the form of infrared excess emission, and for one white dwarf (WD 1145+017) debris clouds were recently seen to pass in front of (transit) the star (see Figure).

As the exoplanetary debris transits its host star, it can be studied in great detail. Multiwavelength transit observations of WD 1145+017 reveal that dust grains below a certain size are absent in the debris clouds. This can be explained by the sublimation of the smallest grains, which have higher equilibrium temperatures than larger bodies. The goal of this project is to model how this process depends on material properties. By understanding these dependencies, the observed minimum grain size can be used to probe the composition of the exoplanetary material.

Project details:
The project would involve writing several small computer programs to solve the following tasks: (1) finding dust temperatures as function of grain size for different optical properties of the dust material (i.e., solving the power balance of incoming and outgoing radiation, using Mie theory to calculate the optical properties of the dust); (2) computing grain survival timescales against sublimation as function of grain size, for different sublimation parameters corresponding to refractory materials; (3) predicting the size distribution of the dust from the balance between the production and destruction of dust by collisions and sublimation; and (4) estimating how transit depths depend on wavelength from the derived grain size distribution, and comparing this with existing observational constraints.

Skills required:
The project is mathematical and computational in nature, involving the development of simple numerical models, using programs written by the student. Some programming experience would be advantageous, but is not essential. Attendance of the Planetary System Dynamics course would be beneficial.

Useful references:
Figure 1: Light curve of white dwarf star WD 1145+017, showing the transits of multiple clouds of debris (Gaensicke et al. 2016).
31. Thermal emission from eccentric dust populations around white dwarfs

Supervisor I: Rik van Lieshout (H23, lieshout@ast.cam.ac.uk)
Supervisor II: Amy Bonsor (H31, abonsor@ast.cam.ac.uk)
UTO: Mark Wyatt (H37, wyatt@ast.cam.ac.uk)

Project summary:
As stars evolve off the main sequence to eventually become white dwarfs (WDs), the planetary systems they host undergo changes. The mass loss experienced by the star during the giant branches causes the gravitational influence of planets on each other and on small bodies like asteroids and comets to become more important. As a result, planetary material can be scattered or perturbed onto highly eccentric, star-grazing orbits during the WD phase. Bodies that end up on such orbits are tidally disrupted when they pass too close to the WD. This leaves behind a highly eccentric ring of debris that stretches out from inside the tidal disruption zone to the outer parts of the remnant planetary system.

The dust in an eccentric ring of tidal debris will gradually spiral into the WD under the action of radiation forces (specifically, Poynting-Robertson drag; Veras et al. 2015). As the ring contracts and circularises, the dust absorbs and emits stellar radiation, which manifests itself as an excess of infrared emission in the WD’s spectrum. The goal of this project is to model this thermal emission from dust on contracting eccentric orbits (see, also, Wyatt 2005; Stone et al. 2015), and to investigate whether it can explain the infrared excesses seen for some WDs (see Figure).

Project details:
The project would involve writing a computer program that (1) follows the evolution of the orbital elements of a dust grain in orbit around a WD due to Poynting-Robertson drag and (2) calculates the resulting thermal emission spectrum of a population of such dust grains. In a next step, synthetic spectra generated by this program would be compared with observed infrared photometry of WDs, using optimisation techniques to find the best-fitting dust population. Finally, the results would be analysed to assess whether the proposed scenario can explain the observations.

Skills required:
The project is mathematical and computational in nature, involving basic manipulations of equations and the development of numerical models, using computer programs written by the student. Some programming experience would be advantageous. Attendance of the Planetary System Dynamics course would be beneficial.

References:
Figure 1: Spectrum of white dwarf G29-38, showing a prominent infrared excess (Farihi 2016).
32. The Hunt for Ultraluminous X-ray Pulsars

Supervisor I: Dominic Walton (Hoyle 27, dwalton@ast.cam.ac.uk)
Supervisor II: George Lansbury (Hoyle 51, gbl23@ast.cam.ac.uk)
UTO: Andrew Fabian (Hoyle 54, acf@ast.cam.ac.uk)

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 three 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 search for additional ultraluminous X-ray pulsar candidates to help grow this new and currently tiny sample.

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 three such sources are currently known: M82 X-2 (Bachetti et al. 2014), NGC 7793 P13 (Fuerst et al. 2016, Israel et al. 2017a) and NGC 5907 ULX (Israel et al. 2017b), 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.

Growing this sample will be a key step in understanding these remarkable sources further. However, identifying additional pulsar ULXs is technically challenging; although they are intrinsically very luminous, their vast extragalactic distances typically make them too faint for X-ray pulsations to be detected. Furthermore, in some of the known pulsar ULXs, the pulsations appear to come and go between observing epochs (the reason for this is currently unknown). Additional means of identifying pulsars among the broader ULX sample are therefore required. One thing the three known ULX pulsars have in common is extreme long-term variability. While they are typically extremely bright, all three also show periods where their flux drops by a factor of ≥100. The primary goal of this project is to search the broader ULX population for other sources that show similarly strong variability, and therefore to identify new ULX pulsar candidates.
Project details:

The student will first work on compiling long-term, multi-mission X-ray lightcurves for the known population of ultraluminous X-ray sources, using publicly available data from the XMM-Newton, Swift, Chandra, Suzaku and NuSTAR satellites. These will then be analysed in a very simple manner to search for sources that show similar long-term behaviour to the known ULX pulsar systems. More detailed analyses (e.g. multi-epoch spectroscopy) of interesting individual candidates identified during the project may follow, depending on progress.

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

Skills required:

The project involves utilizing data from a variety of sources; basic programming will be required.

Useful references:

33. Mapping Galactic Planetary Nebulae with Gaia

Supervisor: Nicholas A Walton (naw@ast.cam.ac.uk /H37), UTO: Mike Irwin, (APM 1A, mike@ast.cam.ac.uk)

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

The ESA Gaia satellite was launched in December 2013. Over the 5 years of its nominal mission it will map the positions, motions, and parallaxes (hence distances) to over a billion stars in the Milky Way. It is sensitive to objects to a limiting Gaia magnitude of $G=20.7$, achieving parallax errors of a few tens of microarcsecs for $G=15$ Solar type stars.

The first major Gaia Data Release (Gaia DR1) was released Sept 2016, providing parallax information for $\sim 2$ million objects brighter than $G \sim 11.5$ and positional information for over 1 billion objects (mainly stars) to $G=20.7$. Apr 2018 will see the release of Gaia DR2, with full five parameter astrometry for over 1 billion sources, down to a magnitude limit of $G=20.7$.

Gaia is optimised for the detection of point sources, and in general is not sensitive to extended objects (with sizes $\geq 0.5$ arcsec). However, Gaia is able to resolve structure within extended objects. This is demonstrated by commissioning observations of the large PN NGC 6543, where the complex nebula is decomposed by Gaia into thousands of individual mapping points. Thus Gaia may measure distance to the PN$_i$ by detection of features in the nebula instead of detection of the central star.

This project will investigate the number of Milky Way PN central stars that will be observable by Gaia, along with estimations of the distance errors that will be achieved for those detectable by Gaia. This will prepare for an analysis of how Gaia will improve the overall estimation of the PN Luminosity Function (PNLF), based on properties of local PN. This impacts on the use of PN as standard candles, and their use in providing a standard distance technique applicable to both young (population 1) and old (population 2) galaxies.

In addition the project will investigate the potential of Gaia DR1 and the upcoming Gaia DR2 in the detection of structure within PN to allow mapping of the complex dynamics of many extended Galactic PN throughout the Milky Way. This will set precise limits on the expansion rates in a representative sample of PN, thus lifetimes, and hence enable an accurate population study of Milky Way PN to be constructed.

**Nature of the Project Work:** Planetary Nebulae Distance Scale

1. Generate a catalogue of PN with central stars observed by Gaia in Gaia DR1, assessing detections of both central stars and surrounding nebulae. This will involve collating a range of basic data about each PN, including sizes and fluxes. For PN not detected directly by Gaia, the project will include use of Gaia detections of nearby stars, and use of the reddening and/or Ha surface brightness techniques to determine distance to the PN. The baseline catalogue of PN is taken from the Hong Kong/AAO/Strasbourg H-alpha PN database.

2. Generate a catalogue of PN with central stars potentially contained within Gaia DR2, assessing detections of both central stars and surrounding nebulae. (The input catalogue can be generated in advance of the release of Gaia DR2. With the publication of that, a rapid initial assessment of objects published in Gaia DR2 will be possible in April 2018).

3. Estimate improvements to distance estimates for those PN

4. Investigate likely proper motion estimates from 1st (summer 2016) and final Gaia data releases, using Hubble Space Telescope imagery as the baseline images.

The project will involve extensive use of ESA Gaia data (http://gea.esac.esa.int/archive/), Gaia DR1 will be available during the project, with the possibility to include some preliminary results from Gaia DR2 which is due to be released in April 2018 (thus shortly before submission of the final project report).
References

- An example of early observations of the Cat’s Eye PN by Gaia can be found at http://www.cosmos.esa.int/web/gaia/iow_20141205
- The Gaia Data Release 1 parallaxes and the distance scale of Galactic planetary nebulae, Stanghellini et al, 2017, New Astronomy, 57, 6

Figure 1: The image shows the source densities of objects in the Gaia Data Release 1. The image is annotated with the location of a range of bright galaxies, open clusters and globular clusters. The Gaia scanning law footprint is seen imprinted in this image. Planetary Nebulae will be visible over the whole sky, with a concentration of objects in the Galactic Plane. Gaia image credit: ESA/Gaia/DPAC
34. Carbon stars in the Gaia-ESO Survey

| Supervisor I: Clare Worley (H24, ccworley@ast.cam.ac.uk) |
| Supervisor II: Anais Gonneau (H21, agonneau@ast.cam.ac.uk) |
| UTO: Gerry Gilmore (H47, gil@ast.cam.ac.uk) |

Project summary:
To investigate the origin of the photometric behaviour, and to determine the fundamental parameters of our Gaia-ESO sample of carbon stars (e.g., temperature and metallicity). We will compare our observed spectra with available new atmospheric models. A previous study was done at “low-resolution” (R ~ 2000), focusing on the shape of the spectra. This new analysis will focus on the molecules to find which ones are not well reproduced in the models and to improve them.

Project description:
Carbon stars are those AGB stars with a ratio of carbon to oxygen abundance larger than 1. Standard population synthesis codes assign spectra to locations along a stellar evolutionary track based on effective temperature and surface gravity. For C stars, at least one extra parameter is required, such as the C/O ratio or the pulsation properties. Gonneau et al. 2016 found that the stars show bimodal behaviour when (J - K) is larger than 1.6. At a given near-infrared colour in addition to the “classical” carbon stars, another family of spectra emerge, characterized by the presence of an absorption feature at 1.53 μm (usually associated to HCN and C2H2). Hot circumstellar dust emission in the near-infrared may help to explain the properties of the stars showing this feature. Many candidate carbon stars are indicated by “flags” in the Gaia-ESO Survey.

Background:
New facilities such as the JWST and the E-ELT will widen the discovery space in extragalactic research, with an enhanced sensitivity in the infrared. The stars whose emission is most important at these wavelengths are cool giants, red supergiants and asymptotic giant branch (AGB) stars.

Project details:
Identify stars flagged as C-type in the Gaia-ESO Survey data, and compare the spectra to the available models. Quantify the agreement and differences.

Some representative spectra of carbon stars, taken from Gonneau et al. 2016. The grey bands mask the regions where telluric absorption is strongest.
35. Modelling the stochastic accretion of differentiated asteroid fragments onto white dwarfs

Supervisor I: Mark Wyatt (H37, wyatt@ast.cam.ac.uk)
Supervisor II: Amy Bonsor (H31, amy.bonsor@gmail.com)
UTO: Mark Wyatt

Project summary:
The aim of the project is to develop a numerical model to explain the compositional diversity of the pollution seen in White Dwarf atmospheres that originates in the accretion of exo-asteroids.

Background:
White Dwarf atmospheres are sensitive probes of the composition of exoplanetary material. This is because their thin convection zones mean that following the accretion of even a small asteroid by the star, the stellar spectrum shows evidence for the metals present in the accreted body. Eventually these metals sink on a timescale that ranges from days to 10s of Myr, depending on the star’s age and its dominant atmospheric component (H or He). Roughly 30% of White Dwarfs show evidence for such pollutants in their atmospheres (Farihi 2016).

This pollution is usually detected by an overabundance of Ca, but a growing number of White Dwarfs have overabundances measured in multiple species (e.g., Hollands et al. 2017). These observations show that the accreted material is on the whole chondritic, and so similar to asteroids in the Solar System (Jura & Young 2014). However, there is a surprising diversity which is interpreted as evidence that the asteroids that are being accreted are fragments of differentiated bodies, and so show compositions that can be interpreted as core-like (e.g., Fe-rich) or mantle-like (e.g., Si-rich), much like the asteroids in the Solar System. Fig. 1 (left) shows a recent compilation of our current knowledge of the inferred compositional diversity.

Fig. 1: (Left) Distribution of compositions of pollutants in White Dwarf atmospheres. The relative abundances of Fe, Si and Mg have been used to derive the fraction of the pollutants that are from core-like vs mantle-like material. (Right) The distribution of accretion rates inferred from the mass of pollutants in White Dwarf atmospheres. The dependence of the inferred accretion rates on the time for metals to sink out of the atmosphere is fitted well by a model in which the asteroids are accreted stochastically from a size distribution (Wyatt et al. 2014).
Project details:
An important question in understanding this phenomenon is the size of the bodies that are being accreted. It is often implicitly assumed that we are seeing the aftermath of the accretion of a single asteroid. In this case the range of observed compositions simply reflects the diversity of exo-asteroid compositions, which can be vary within a system. However, it was recently shown that the way the total mass of metals in White Dwarf atmospheres varies as a function of sinking time points to the stochastic accretion of multiple planetesimals from a size distribution (Wyatt et al. 2014; see Fig. 1 right). If the pollution arises from many small bodies the observed composition in Fig. 1 left would be the average of the parent asteroid belt and it would be unlikely to measure extreme compositions (e.g., a pure core-like composition).

The aim of the project is to incorporate compositional diversity in the model of Wyatt et al. (2014) to compare its predictions with the observations in Fig. 1 left. The first step in the modelling process is to recreate the 2014 model. This is a Monte Carlo model in which the number of asteroids in different size bins that are accreted in a given timestep is chosen probabilistically, with the mass remaining in the atmosphere decaying exponentially. The second step is to assume that the accreted bodies have an associated composition, from a parameterised distribution. It will then be possible to track the composition of the atmospheric pollutants as a function of time in individual systems and assess if this composition has a dependence on White Dwarf properties. The next step is to fit the observed compositional diversity in Fig. 1 left. If this is possible then constraints will be derived on the underlying distribution of asteroid compositions, with implications for the differentiation of exo-asteroids and how to interpret observed compositions. Finally it will be possible to explore the proposal of Malamud & Perets (2017) that the low volatile content of the accreted material (e.g., Xu et al. 2017) arises because the volatiles accrete on a shorter timescale than the refractories. This can be included in the model by having a disk lifetime that is composition dependent.

Skills required:
Programming knowledge required. Attendance of the Planetary System Dynamics course would be beneficial but not essential.

References:
Farihi 2016, New Ast. Rev., 71, 9
Jura & Young 2014, AREPS, 42, 45
APPENDIX

Part III Research Projects – 2017-2018

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 Monday and Wednesday or Tuesday and Thursday of Michaelmas Full Term (9/11 or 10/12 October 2017).

Choice of up to five projects, in rank order, should be handed to the Course Secretary by noon on the second Friday of Michaelmas Full Term (13 October 2017). 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 (17 October 2017). 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/UTO, must be handed to the teaching office no later than the last day of Michaelmas Full Term (1 December 2017). 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 Wednesday, Thursday and Friday of Lent Term (14, 15 and 16, March 2018). 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 18 April 2018. An eighth Supervision, to discuss the draft report, should take place no later than the first Tuesday of Easter Full Term (24 April 2018).

Two copies of the final project report must be handed, in person to the teaching office no later than 4.30 pm on the second Tuesday of Easter Full Term (1 May 2018). 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 Wednesday, Thursday or Friday of Easter Full Term (2, 3 or 4 May 2018). 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 19 June 2018.

Project reports may be collected from the teaching office after 9.00 am on Wednesday 19 June 2018.

**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. The report may also include some material in the form of an Appendix subject to the page limits set out below.
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 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 the Examinations it 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

Email: +*@ast.cam.ac.uk unless given otherwise
<table>
<thead>
<tr>
<th>#</th>
<th>Project Title</th>
<th>pp</th>
<th>Contacts</th>
</tr>
</thead>
</table>
| 1  | Einstein rings of strongly lensed QSOs: properties of AGN hosts at z~2 and new constraints on the lensing potential | 1   | Auger, Matthew  
Email: mauger  
McMahon, Richard  
Email: rgm |
| 2  | Quasars and Friends: Exploring the environments of the most massive supermassive black-holes in the early Universe | 2-3 | Banerji, Manda  
Email: mbanerji  
Hewett, Paul  
Email: phewett |
| 3  | Belts of asteroids and comets: do they survive around giant stars?            | 4-5 | Bonsor, Amy  
Email: abonsor  
Wyatt, Mark  
Email: wyatt |
| 4  | AGN feedback: Quenching and triggering of star formation in disc galaxies    | 6-8 | Bourne, Martin  
Email: mbourne  
Sijacki, Debora  
Email: deboras |
| 5  | Improving visualisation of time-series and large data sets                    | 9-10| Hourihane, Anna  
Email: aph  
Breedt, Elme  
Email: ebreedt  
Gilmore, Gerry  
Email: gil |
| 6  | The ablation of planetesimals in gas giant planets formed through gravitational instability | 11-12| Clarke, Cathie  
Email: cclarke  
Madhusudhan, Nikku  
Email: nmadhu |
| 7  | An inverse distance ladder approach to the Hubble constant                    | 13-15| Efstathiou, George  
Email: gpe  
Gratton, Steven  
Email: stg20 |
| 8  | Thermal instability in the circumgalactic medium of z~6 galaxies              | 16-18| Fiacconi, Davide  
Email: fiacconi  
Sijacki, Debora  
Email: deboras |
| 9  | Spin alignment in circumbinary discs                                          | 19-21| Sijacki, Debora  
Email: deboras  
Fiacconi, Davide  
Email: fiacconi |
| 10 | Are the first stars hiding behind later pollution?                            | 22-23| Gilmore, Gerry  
Email: gil  
Worley, Clare  
Email: ccworley |
| 11 | The role of stellar evolution & nucleosynthesis in the formation of white dwarfs: how updated stellar models may affect yields of novae explosions. | 24-25| Halabi, Ghina  
Email: gmh  
Hewett, Paul  
Email: phewett |
| 12 | Host galaxy properties derived from a statistical analysis of quasar spectra photometry | 26-27| Hewett, Paul  
Email: phewett  
Banerji, Manda  
Email: mbanerji |
| 13 | A systematic search for transiting Exocomets                                  | 28-29| Hodgkin, Simon  
Email: sth  
Kennedy, Grant  
Email: gkennedy  
Wyatt, Mark  
Email: wyatt |
| 14 | Connection between planets and spiral arms in protoplanetary discs            | 30-31| Juhasz, Atilla  
Email: juhasz  
Rosotti, Giovanni  
Email: rosootti  
Clarke, Cathie  
Email: cclarke |
| 15 | Expanding the observational frontier of planet formation                      | 32-33| Kama, Mihkel  
Email: mkama  
Clarke, Cathie  
Email: cclarke |
| 16 | The environments of supermassive black hole growth: studying the host galaxies of high energy X-ray AGN | 34-35 | Lansbury, George  
Email: gb123  
Banerji, Monda  
Email: mbanerji  
Fabian, Andy  
Email: acf |
| 17 | High-resolution spectroscopy of a hot Jupiter | 36-37 | Madhusudhan, Nikku  
Email: nmadhu  
Hodgkin, Simon  
Email: sth |
| 18 | Measuring the sizes of ionized hydrogen near zones in high redshift quasars in the epoch of reionisation | 38-39 | McMahon, Richard  
Email: rmg  
Pons, Estelle  
Email: pons |
| 19 | What is the optimal primary mirror shape for a space telescope? | 40-41 | Parry, Ian  
Email: irp  
Irwin, Mike  
Email: mike |
| 20 | Extreme matter accretion onto black holes in ultraluminous X-ray sources and active galactic nuclei | 42-43 | Pinto, Ciro  
Email: cpinto  
Fabian, Andy  
Email: acf |
| 21 | The fight between cooling and heating in clusters of galaxies | 44-45 | Pinto, Ciro  
Email: cpinto  
Fabian, Andy  
Email: acf |
| 22 | Seeing the cosmic web in Lyman-alpha emission | 46-47 | Puchwein, Ewald  
Email: puchwein  
Haehnelt, Martin  
Email: haehnelt |
| 23 | Ultra-fast outflows from tidal disruptions of stars by massive black holes | 48-49 | Reynolds, Chris  
Email: csr12@cam.ac.uk  
Pinto, Ciro  
Email: cpinto |
| 24 | Grain growth in proto-planetary discs in binary systems | 50-52 | Rosotti, Giovanni  
Email: rosootti  
Clarke, Cathie  
Email: cclarke |
| 25 | Detecting the signatures of planet formation around low mass stars | 53-54 | Rosotti, Giovanni  
Email: rosootti  
Clarke, Cathie  
Email: cclarke |
| 26 | The gravitational sphere of influence of the black hole at the centre of NGC 4472 | 55-56 | Russell, Helen  
Email: hr27  
Fabian, Andy  
Email: acf |
| 27 | Dynamical models of globular clusters | 57-58 | Sanders, Jason  
Email: jls  
Evans, Wyn  
Email: wne |
| 28 | The shapes of globular clusters from Hubble photometry | 59-60 | Sanders, Jason  
Email: jls  
Evans, Wyn  
Email: wne |
| 29 | Volcanism on hot super-Earths: how and why? | 61-62 | Shorttle, Oliver  
Email: os258@cam.ac.uk  
Madhusudhan, Nikku  
Email: nmadhu |
| 30 | Sublimating exoplanetary material around white dwarfs | 63-64 | van Lieshout, Rik  
Email: lieshout  
Wyatt, Mark  
Email: wyatt |
| 31 | Thermal emission from eccentric dust populations around white dwarfs | 65-66 | van Lieshout, Rik  
Email: lieshout  
Wyatt, Mark  
Email: wyatt |
| 32 | The hunt for ultraluminous X-ray pulsars | 67-68 | Walton, Dom  
Email: dwalton  
Fabian, Andy  
Email: acf |
| 33 | Mapping galactic planetary nebulae with Gaia | 69-70 | Walton, Nic  
Email: naw  
Irwin, Mike  
Email: mike |
| 34 | Carbon stars in the Gaia-ESO Survey | 71-72 | Worley, Clare  
Email: ccworley  
Gilmore, Gerry  
Email: gil |
| 35 | Modelling the stochastic accretion of differentiated asteroid fragments onto white dwarfs | 73-74 | Wyatt, Mark  
Email: wyatt  
Bonsor, Amy  
Email: abonsor |
<table>
<thead>
<tr>
<th>Name</th>
<th>Email+*</th>
<th>Phone</th>
<th>Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger, Matthew</td>
<td>mauger</td>
<td>(3)37529</td>
<td>Hoyle 40</td>
</tr>
<tr>
<td>Banerji, Manda</td>
<td>mbanerji</td>
<td>(3)37549</td>
<td>Kavli 19</td>
</tr>
<tr>
<td>Bonsor, Amy</td>
<td>abonsor</td>
<td>(7)65845</td>
<td>Hoyle 31</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>Clarke, Cathie</td>
<td>cclarke</td>
<td>(3)39087</td>
<td>Hoyle 10</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>Fiacconi, Davide</td>
<td>fiacconi</td>
<td>(7)60795</td>
<td>Kavli 16</td>
</tr>
<tr>
<td>Gilmore, Gerry</td>
<td>gil</td>
<td>(3)37506</td>
<td>Hoyle 47</td>
</tr>
<tr>
<td>Gratton, Steven</td>
<td>stg20</td>
<td>(7)65849</td>
<td>Kavli 7</td>
</tr>
<tr>
<td>Gonneau, Anais</td>
<td>agonneau</td>
<td>(3)37504</td>
<td>Hoyle 21</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)37551</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>Juhasz, Atilla</td>
<td>juhasz</td>
<td>(7)66095</td>
<td>Hoyle 22</td>
</tr>
<tr>
<td>Kama, Mihkel</td>
<td>mkama</td>
<td>(7)66098</td>
<td>Hoyle 25</td>
</tr>
<tr>
<td>Kennedy, Grant</td>
<td>gkennedy</td>
<td>(3)37504</td>
<td>Hoyle 36</td>
</tr>
<tr>
<td>Kral, Quentin</td>
<td>qkral</td>
<td>(7)65845</td>
<td>Hoyle 31</td>
</tr>
<tr>
<td>Kulkarni, Girish</td>
<td>kulkarni</td>
<td>(7)66651</td>
<td>Kavli 16</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)6619</td>
<td>Hoyle 18</td>
</tr>
<tr>
<td>McMahon, Richard</td>
<td>rgm</td>
<td>(3)37519</td>
<td>Hoyle 49</td>
</tr>
<tr>
<td>Parry, Ian</td>
<td>irp</td>
<td>(3)37092</td>
<td>Hoyle 57</td>
</tr>
<tr>
<td>Pinto, Ciro</td>
<td>cpinto</td>
<td>(3)39281</td>
<td>Hoyle 56</td>
</tr>
<tr>
<td>Pons, Estelle</td>
<td>pons</td>
<td>(7)60792</td>
<td>Hoyle 55</td>
</tr>
<tr>
<td>Puchwein, Ewald</td>
<td>puchwein</td>
<td>(3)37533</td>
<td>Kavli 20</td>
</tr>
<tr>
<td>Reynolds, Chris</td>
<td><a href="mailto:csr12@cam.ac.uk">csr12@cam.ac.uk</a></td>
<td>(3)30803</td>
<td>Hoyle 15</td>
</tr>
<tr>
<td>Rosotti, Giovanni</td>
<td>rosoni</td>
<td>(7)60799</td>
<td>Hoyle 21</td>
</tr>
<tr>
<td>Russell, Helen</td>
<td>hrr27</td>
<td>(3)30895</td>
<td>Hoyle 53</td>
</tr>
<tr>
<td>Sanders, Jason</td>
<td>jls</td>
<td>(3)37542</td>
<td>Hoyle 33</td>
</tr>
<tr>
<td>Sijacki, Debora</td>
<td>deboras</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>van Lieshout</td>
<td>lieshout</td>
<td>(7)66095</td>
<td>Hoyle 23</td>
</tr>
<tr>
<td>Walton, Dom</td>
<td>dwalton</td>
<td>(7)60793</td>
<td>Hoyle 51</td>
</tr>
<tr>
<td>Walton, Nic</td>
<td>naw</td>
<td>(3)37503</td>
<td>Hoyle 37</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>