Researcher Exchanges in Radio Astronomy – University of Manchester projects January 2019

1. Unveiling star formation across cosmic time: Predictions for the SKA

Supervisor: Dr Rowan Smith

The SKA will revolutionise our understanding of how galaxies form and transform their gas into stars by mapping HI 21cm line emission with exquisite detail and sensitivity. With the SKA it will be possible to peer back across cosmic time and study the interstellar medium (ISM) in a whole range of galaxy types and metallicities, including irregular dwarf galaxies such as those found in the early universe. However, to truly unlock the power of such observations it is crucial to have similarly advanced models to compare the data too.

In this project we will use cutting edge simulations of the ISM in different galaxy types with the Arepo MHD code to study where atomic hydrogen gas is located and when it transforms into molecular H2. The simulations are resolved down to sub-pc scales and include a detailed model of the chemistry of the warm and cold gas. Using these simulations we will perform post-process radiative transfer simulations with the Polaris and LIME codes to predict the HI emission that would be seen from different galaxy types with the SKA. In order to get a full view of the gas life-cycle in such galaxies we will then also calculate the molecular gas emission that would be seen in CO with ALMA, and the CII emission that could be seen in nearby galaxies with SOFIA. Using our simulations and these synthetic emission maps we will aim to make testable predictions about the evolution of galaxies from low-metallicity dwarfs, to grand design spirals, to star-burst galaxies and how they transform their gas into stars.

This project would be suitable for a PhD student or post-doctoral fellow either with a background in numerics or observations.

2. Optimizing Interferometric Data Processing with GPUs

Supervisors: Prof. Gary Fuller & Prof. Anna Scaife

Within increasing spatial resolution and numbers of spectral channels, the task processing of interferometric data to produce science products is increasingly time consuming and computationally intensive. One novel approach to this issue is through the use of graphic processing units (GPUs) which allow massive parallelization of the data processing. The gridding and Fourier transform part of the imaging process is highly parallelizable, and is therefore well-suited to algorithms that utilise GPU hardware. However, the mostly commonly used radio astronomy deconvolution algorithm, CLEAN, is less well suited and new deconvolution techniques need to be explored. The JBCA Centre for Interferometry Excellence, ICE, has been leading the development of the GPU-based imaging pipelines for SKA and the UK ALMA Regional Centre (ARC) Node at JBCA have been exploring the application of these techniques for imaging ALMA data.

This project will involved working with members of ICE and the UK ARC Node to implement and improve the GPU processing of data for both ALMA and SKA, especially in the area of deconvolution.

The work will be undertaken on a small cluster of dedicated high speed work stations equipped with nVidia K40 GPU cards (each card containing 2880 GPU cores) in the UK ARC Node as well as a range of other GPUs available within ICE. This project would suit a PhD student or post-doctorial fellow with experience in radio interferometer data processing techniques as well as an interest and good skills in programming.

3. On-Demand Processing of Archival Interferometric Data

Supervisors: Prof. Gary Fuller & Prof. Anna Scaife

Broadband radio interferometric datasets are scientifically rich and versatility, allowing the production of a wide range of science products well beyond their original science goal. The science available from archives of interferometric data increases with time as calibration and imaging techniques improve and the volume of data increases, for example, enabling science which builds on multiple initially individual projects. Extracting this science requires the ability for an archive user to identify datasets of interest and image them to match their science requirements, such as at given spatial or spectral resolution or to produce line ratio cubes or spectral index images using data from different projects. Such versatile archive access and `on-demand' data processing is beyond the scope of any existing telescope archive, but is essential to exploit the full science capabilities of instruments like SKA and ALMA.

This project will investigate the requirements for, and initial design and implementation of, an `on-demand' processing archive to allow users to retrieve datasets on the basis of their science requirements and use the latest calibration and processing techniques to produce science ready outputs `on-demand'. To gain experience with the required data processing and current state of the art archives, this project will work closely with the current ESO ALMA Archive Reimaging Project through the UK ALMA Regional Centre (ARC) Node. The system will initially be designed and developed for ALMA as it currently has the most complete and well-defined archive but would then be extended to eMERLIN. Both of these would act as demonstrations of how such a system will eventually be implemented for SKA. This project would suit a PhD student or post-doctorial fellow with experience in the techniques of processing interferometer data and interest and good skills in programming.

4. Time Domain Studies of The Radio Emission from Star Forming Regions

Supervisor: Prof. Gary Fuller

The radio emission from young stars probes the inner circumstellar regions of the protostars where material is accreted on to the forming star, the star is connected to its circumstellar disk and outflows are launched. It is the processes in the circumstellar regions which ultimately control how a protostar grows to its final mass. However, the radio emission from accretion, outflow and stellar flares and, for more massive objects, changes in the ionization of their envelopes, changes with time and understanding the changes in the emission provides important constraints on the star formation process. Recent improvements in the sensitivity of radio telescopes have started to allow detailed studies of radio variability of young stars for the first time. The initial studies have shown that the radio emission is providing a different probe of the circumstellar regions from the variable x-ray emission which has been previously studied.

This project will use existing radio telescopes, particularly the JVLA, ALMA and possibly ATCA and eventually MeerKAT64, to study the radio variability of young stars in clusters over a range of frequencies and timescales from minutes to years. The initial goal will be to determine the nature of the variability in both time and observing frequency, then using models to constrain the physical processes which produce the radio emission. Ultimately the experience gained from these studies will be applied to surveys with the SKA. This project would be suitable for a PhD student or post-doctorial fellow.

5. Connecting Star Formation in the Starburst Galaxy NGC253 and Star Forming Regions in the Milky Way

Supervisor: Prof. Gary Fuller

This project will involve using data taken as part the recently approved ALMA large programme ALCHEMI. ALCHEMI is a spectral survey of the starburst galaxy NGC253. It will image the inner 50'' by 20'' (850 pc by 340 pc) of the galaxy at 1'' (17 pc) resolution in ALMA bands 3, 4 6 and 7, covering frequencies from 85 GHz to 366 GHz. These data will provide the most complete molecular inventory yet of an extragalactic source and will provide the templates of the chemistry, excitation and physics of this starburst on GMC scales. The results from ALCHEMI will act as a benchmark for future studies of extragalactic starbursts.

Interpreting many of the results from ALCHEMI will require 'calibrating' the observations of NGC253 against galactic star forming regions to understand the details of the star formation processes which produce the emission from NGC253. This is the goal of this project. The project will involve assisting in producing the science data products from the ALCHEMI observations. These will then be used to compare the properties of the properties of the GMCs in NGC253 with extreme star forming clouds in the Milky Way as well as chemo-physical models of these regions. This will involve using existing data and proposing new observations with a range of telescopes as well producing synthetic observations from models. A detailed and complete understanding of the starburst in NGC253 will help provide a firm basis for the prediction of the emission and star formation process which will be observable with SKA in the future. This project would be suitable for a PhD student or post-doctorial fellow.

6. Pushing the Noise Limit: Low Noise Amplifiers for Radio Telescopes

Supervisor: Prof. Gary Fuller & Prof. Danielle George

Low noise amplifiers (LNAs) are critical components of receivers for radio telescopes. They offer a number of important advantages over competing technologies such as operating at 20K rather than 4K as well as being better suited for use in large scale imaging array receivers. Recent advances in technology have allowed the development of LNAs which operate at much higher frequencies than previously possible. This is an opportunity to join the Advanced Radio Instrumentation Group in the Schools of Physics & Astronomy and Electrical & Electronic Engineering and the newly established joint research laboratory for Radio Astronomy Advanced Instrumentation Research (RAAIR) in 3 research areas:

5.1) Project LNA1:

This project will involve designing and testing high performance, wide bandwidth, LNAs at frequencies of up to 300 GHz, and beyond, for use in both single pixel and array receivers on the world's biggest telescopes. The project will build on our recent work in designing and implementing a world-leading LNA for a new receiver band on the ALMA telescope (www.almaobservatory.org), the world's largest telescope operating at millimetre and submillimetre wavelengths. There will also be opportunities to work on LNAs at lower frequencies for the new generation radio telescope, the Square Kilometre Array (SKA; skatelescope.org). In addition, there may be the opportunity to contribute to the design, integration, testing and deployment of complete receiver systems for operation on a range of radio telescopes.

5.2) Project LNA2:

In order to continue pushing the technological and scientific boundaries we seek to improve our understanding of the performance of low noise amplifiers. A major factor in improving the performance of devices is our understanding of the solid-state physics of the materials and processing used to manufacture them. This project will involve studying the physics of devices from a range of suppliers with whom we collaborate and investigating how the fundamental performance of the processing and devices can be improved. There will also be the opportunity to work with new novel materials such as graphene and related 2-D materials to produce transistor for future, high performance generations of LNAs.

5.3) Project LNA3:

Optimising the design of low noise amplifiers to produce the performance required for particular applications is a time-consuming task with the need to balance multiple competing objectives. This project will investigate machine learning techniques as a way to speed and improve LNA design. Initially the project will involve work with components and designs at frequencies around 1.5 GHz, where there is abundant information to train computational methods but the eventual goal is to apply the methods to devices at frequencies up to 300 GHz and above.

These three projects would be suitable for a PhD student or post-doctoral fellow.

7. The Formation of Massive Stars in the Most Extreme Clumps

Supervisor: Prof. Gary Fuller

Massive stars form in the most massive clumps in molecular clouds. Recent observations have identified a sub-sample of clumps which are so dense that they are opaque at 70 microns and seen in absorption against the diffuse 70 micron background emission. The most massive of these regions were believed to contain pristine massive cores which had not yet formed any stars and to be the precursors to massive stars. However, recent studies of some of these regions have shown that they are already fragmented and contain young stars. The nature of these stars is unclear and in particular it is unknown if some of these stars could still evolve in to massive stars. This project will use observations from ALMA and other radio telescopes to study the nature of these 70 micron-dark massive regions and the protostars within them with the aim of answering the question of whether initial fragmentation and the formation of possibly low mass protostars is an impediment to the future formation of massive stars.

8. The Evolution of Massive Protostars

Supervisor: Prof. Gary Fuller

The astrochemistry of the circumstellar regions of massive protostars is a sensitive probe of the evolutionary status of the protostars. An ALMA survey of 38 protostars shows a wealth of spectral features from a rich range of simple and complex organic molecular species. This project will involve working with these data and models of the astrochemistry to investigate the spatial distribution of these species to study the structure and evolution of the circumstellar regions of these sources with the aim of disentangling the effects of direct heating from the central protostar and shocks from the outflows. The project will also involve obtaining and analysing additional ALMA data on this sample to study tracers of the cold molecular component of the circumstellar material.

9. Modelling the Extragalactic Radio Sky in the SKA era

Supervisors: Dr Scott Kay (JBCA) & Dr Anna Bonaldi (SKAO)

The SKA will transform our understanding of the extragalactic sky at radio wavelengths, allowing us to observe distant star-forming galaxies and measure the growth of large-scale structure through the gravitational lensing of these objects by intervening dark matter. Of central importance to these goals is our ability to construct reliable models of the extragalactic radio source population. As a result, we have recently started developing a new model, T-RECS, which combines the predicted dark matter distribution from cosmological N-body simulations and observational constraints from existing radio data, to compute realistic model radio skies. We are seeking a PhD student to help us develop and test these models further, adapt them to new simulations as they become available, and use them to make predictions for a range of extragalactic/cosmology applications of relevance to the SKA.

10. Planetary nebula obscuration

Supervisor: Prof Albert Zijlstra (JBCA)

Planetary nebulae are ionized shells of gas surrounding an evolved star. The shells were ejected by the star in its death throes. The ionized gas emits both radio and optical radiation, and the line and continuum emission are ideal for mass measurements and abundance determinations. The bright [O III] line at 5007A, which gives the Planetary nebula its characteristic green colour, is used for measuring distance to other galaxies. This requires measuring the extinction caused by dust in the interstellar medium. This is done either using the ratios of the strengths of the various hydrogen lines, or by comparing the radio emission (not affected by extinction) to the hydrogen lines. The two measurements give different answers and this discrepancy has been an unsolved problem for the past 25 years. The project involves analysing a complete set of radio data from the Very Large Array, to obtain the most accurate radio fluxes. They will be combined with optical line strengths compiled by the group at the University of Hong Kong, to study this discrepancy in detail. Photo-ionization modelling will be used to show whether the discrepancy is caused by anomalous dust, or by unusual conditions in the ionized nebulae.

11. Pulsar seismology: pulsar timing and the long term behaviour of radio pulsars

Supervisors: Dr Mike Keith & Dr Patrick Weltevrede

PhD project: Radio pulsars are rotating neutron stars, which are observed through pulsations detected as the magnetic pole of the star passes through our line of sight. The rotation of these stars can be tracked with incredible accuracy, with some pulsars having RMS deviations from our models of less than 100 nanoseconds over ten years. However, the complex physical processes behind neutron stars is most apparent through the many cases where pulsars cannot be understood through simple models. Sudden changes in the pulsar spin can appear due to seismic shifts in the superfluid interior; long-term switching between different emission modes indicates complex activities in the magnetosphere.

In this project, you will investigate some of these phenomena through the techniques of pulsar timing. The project will use data from the Jodrell Bank pulsar timing archive, which contains observations of 1500 pulsars with up to 45 year timespans per pulsar. The archive contains 23000 years of pulsar rotation history, and therefore allows for unique studies of the long-term behaviour of radio pulsars.

12. Novel cryogenics for Cosmic Microwave Background experiments.

Supervisor: Prof Lucio Piccirillo

The next generation of Cosmic Microwave Background B-modes polarization experiments will need a significant step forward in a number of technologies. Large format arrays of superconducting detectors (TES, KIDs, etc.) are the preferred choice when experiments need to populate focal planes with hundreds of thousands of pixels. Superconducting detectors require sub-K temperatures to operate in the sensitivity regime required.

In this project you will design, build and test a variety of cryogenic devices and sub-systems, from simple pre-cooling gas heat-switches to novel miniature dilution refrigerators capable of reaching 20-50 mK physical temperatures. You will learn how to operate high-vacuum systems, mechanical coolers and associated low noise thermometry.

13. Exploring extragalactic star formation in the radio, millimetre, and submillimetre

Supervisors: Dr George Bendo & Prof Clive Dickinson

The current generation of submillimetre, millimetre, and radio telescopes, including ALMA, eMERLIN, and JVLA, are opening up a new world in the study of extragalactic astronomy. Combined together, these telescopes can measure emission over a very broad range of the electromagnetic spectrum, detecting fainter emission than and producing sharper images than prior telescopes.

These telescopes have opened up new possibilities in the study of star formation in other galaxies, as free-free emission from ionized gas found in star forming regions can be detected much more easily and as the detection of very faint millimetre and submillimetre hydrogen recombination lines is now feasible. These star formation tracers can be directly linked to the number of recently-formed stars within star forming regions, unlike infrared dust emission or radio synchrotron emission, but the star formation tracers are also unaffected by the dust obscuration that affects optical hydrogen line or ultraviolet stellar emission. Hence, free-free and recombination line emission in the radio, millimetre, and submillimetre bands can be used to measure very accurate star formation rates in the most dusty star forming regions in the universe.

This Ph.D. project is based on working with ALMA, eMERLIN, and JVLA data as well as data from other telescopes to probe star formation in the nearby extragalactic universe. Specific topics for inverstigation include the following:

- Identification of and characterisation of individual photoionization regions within nearby starbursts.
- The construction of and modelling of galaxy spectral energy distributions so as to identify and separate the emission from free-free, synchrotron, and thermal dust emission (as well as the potential to identify other forms of continuum emission).
- The measurement of electron temperatures using a combination of recombination line and free-free continuum emission.
- Comparisons of star formation rates from free-free continuum and radio, millimetre, and submillimetre recombination line emission to rates from ultraviolet, optical, and infrared star formation tracers.

14. Technical projects with School of Electrical and Electronic Engineering

Supervisors: Prof Tony Brown and Dr David Zhang (EEE)

14.1 Low Cost PAF development for SKA 2 (Post-Doctoral)

Develop a 2-D low profile receptor technology for PAF, combined with latest off-shelf low noise amplifiers under cryogenic conditions. The multiple beam forming algorithms will be developed. A feasible solution will be investigated towards SKA 2 with PAF technology of an affordable cost.

14.2 Optical Front-End Development towards full digital arrays (PhD Project)

The project is to develop optical link to the element level for dense aperture array, ready to digitise the received signals from each element locally or remotely. The interface of the front-end output is desirably to be compatible with the existing tile processors for SKA LFAA, in order to use the expertise and back-end technologies developed for LFAA in the higher frequencies. The existing prototypes developed for the mid-frequency aperture array will be used as a starting point for this development.

14.3 Differential Front-End Development (Post-Doctoral)

Differential front-end solutions have the following advantages: 1) Good isolation from the environment; 2) The cancellation of the even-order intermodulation products; 3) Suppression of interference sources at the horizon and high dynamic range; 4) Large common mode rejection. This project will develop a fully differential front-end sub-system of aperture arrays. The latest graphene material will be used to improve the common mode rejection ratio due to its unique characteristics in the microwave frequency band.

15. Synchronisation and Timing for Radio Astronomy Interferometry

Supervisors: Professor Keith Grainge, Dr Althea Wilkinson (& Dr Bassem Alachkar)

In radio interferometric telescopes, such as the SKA, the synchronization and timing (SAT) systems provide frequency and timing signals to the receptors and other parts of the telescope. The stability and accuracy provided by these systems have important impact on the performance of the observatory. The basic SAT stability and accuracy requirements are driven by the astronomical science requirements, covering the radio astronomy functions of the telescope for imaging, pulsar searching and timing, and very long baseline interferometry (VLBI).

This Ph.D. project will investigate the SAT systems for radio astronomy telescopes. It has the following objectives:

- To study the synchronisation and timing requirements in relation with the radio astronomy science requirements
- To review the current techniques, methods, architectures and technology of the synchronisation and timing systems for radio astronomy. To analyse their performance, and to identify the limitations of the current systems.
- To propose a new design that improves the performance
- To develop a prototype that validates the proposed design

The researcher would work closely with the newly established joint research laboratory for Radio Astronomy Advanced Instrumentation Research (RAAIR).