(PhD) Sparsity-based methods for multi-frequency, rotation measure synthesis deconvolution

Supervisors: Prof O. Smirnov (osmirnov@gmail.com)

Recent progress in compressive sensing (CS) methods has yielded a number of deconvolution algorithms based on the sparsity assumption that seem far better at recovering extended emission than CLEAN and its multiscale variations. For example, the MORESANE (Dabbech et al. 2015, arXiv:1412.5387) algorithm as implemented and released by J. Kenyon (Rhodes PhD student, see http://github.com/ratt-ru/PyMORESANE) has already given us the deepest-ever images of Cyg A in S-band (using JVLA data). Other promising algorithms include PURIFY (Carrillo et al. 2014) and LOFAR-CS (Garsden at al. 2015 -- one of the key developers of the latter is joining Rhodes/SKA SA as a postdoc). New work by Ferrari et al. (2015, arXiv:1504.06847, same team as MORESANE) has extended this work into the multi-frequency regime. We propose to develop, jointly with the Ferrari et al. team, a sparsity-based deconvolution method for full-polarization multi-frequency rotation measure (RM) synthesis.

Relevance to MeerKAT and the SKA. MeerKAT and SKA1 will enable wide-band radio observations to unprecedented sensitivity. A lot more faint extended and polarized emission will be detectable, but the wide frequency band makes it crucial to incorporate the frequency and polarization axis into the deconvolution process if the full potential of these instruments is to be realized.

(MSc/PhD) Bayesian Inference for Polarimetric Calibration

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
Prof. R. Taylor (UCT/UWC) (russ@ast.uct.ac.za)

Recent work on BIRO (Bayesian Inference for Radio Observations) by Lochner at al. (2015) and Natarajan et al. (in prep.) has demonstrated the promise of Bayesian inference techniques in the domain of radio interferometric calibration. We now propose to apply BIRO to polarization calibration. Accurate polarization calibration in radio interferometry is a difficult problem, as the instrumental polarization leakage terms interact with the time-variable gain terms, and also need to be disentangled from intrinsic source polarization. The matrix-based radio interferometry measurement equation (RIME) provides a complete mathematical model for forward modelling of this process; inverting the model to go from observed visibilities back to polarization properties is a different matter. The Bayesian approach seems ideally suited to this, its particular strength being the ability to map out correlations between instrumental and scientific parameters while imposing prior constraints.

Relevance to MeerKAT and the SKA. A number of key MeerKAT and SKA1 surveys will rely on accurate polarimetric calibration to achieve their science goals. The problem is especially severe with the linearly polarized feeds employed by KAT-7, MeerKAT and SKA1. Urgent progress on this problem is required.

(MSc) A Practical Survey of Novel and Legacy Radio Interferometry Imaging Algorithms and Packages

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
S. Makhathini (sphemakh@gmail.com)

The quantity of the data that will be produced by the SKA and its pathfinders poses difficult challenges for radio interferometer reduction and imaging techniques. However, on one hand, radio interferometry packages such as MeqTrees and CASA have grown sophisticated enough that we can start addressing some of these issues, and frameworks such as Pyxis and RODRIGUES have enhanced their interoperability and facilitated their deployment on cluster and cloud computing systems, paving the way for powerful and flexible modular data processing pipelines. And, on the other hand, major advances have made in synthesis imaging algorithms and packages. In particular, a lot development has been made on compressive sensing based algorithms, with imagers such as MORESANE (Dabech et a l2014), PURIFY (Carillo et al 2014) and SASIR (Girad et al 2015) showing great promise. There has also been major advances in algorithms based on the CLEAN algorithm (Hogbom 1974), most notably WSCLEAN, and the facet imager BULLSEYE (Hugo in prep). The aim of this project is to do a comprehensive survey of the above mentioned imagers. We wish to look at how these imagers, i) perform under various observing conditions, ii) recover different source distributions, and iii) efficiently use computer resources.

More importantly we wish to gauge their readiness for MeerKAT/ASKAP sized datasets. A byproduct of this research will be an online cloud-based "Beauty Competition" service for systematically evaluating and comparing imaging algorithms.

Relevance to MeerKAT and the SKA. This project will be centered around simulated MeerKAT data. Such a survey can be used to guide the eventual MeerKAT imaging pipeline. RODRIGUES also offers the flexibility to deploy the resulting pipeline on a cloud environment (Google Compute Cloud or Amazon Web Services) as well as the CHPC clusters. Once deployed these these systems, large scale MeerKAT simulations can be readily imaged. The results of the project will provide vital experience for MeerKAT data processing.

(PhD) Understanding the Limits of Interferometric Techniques for Epoch of Reionisation Detection

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
Prof F.B. Abdalla (UCL/Rhodes) (fba@star.ucl.ac.uk)

The Epoch of Reionisation (EoR) is the next frontier for the cosmologist. The faint signal arising from this epoch can be measured by radio interferometers at low frequencies capturing the redshifted signal from the 21cm line. However, an outstanding issue not clearly resolved by any current EoR experiment is that calibration issues could plague this signal and prevent a clear detection from taking place. In particular, it is possible that direction dependent effects (DDEs) will change the nature of this signal and smear any possible detection. We propose to investigate how DDEs affect this cosmological signal, and whether the statistical properties of this signal are maintained after DDEs are calibrated out, and more specifically if the magnitude of the fluctuations is maintained. The student would obtain simulations of the 21cm signal, pass them through a radio interferometry simulator, and obtain visibilities which would be corrupted with a direction dependent signal. This signal would be calibrated with DD-solution algorithms such as SAGECAL or StefCal, and the signal would be remeasured and compared to the original input. The result of this research would place clear constrains on our ability to measure the EoR signal using current and future interferometers, and inform the calibration strategy of future EoR experiments, and

(MSc/PhD) Analyzing The Impact Of Ghosts On Future Cosmological Radio Surveys

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
Prof F.B. Abdalla (UCL/Rhodes) (fba@star.ucl.ac.uk)

Ghosts are calibration artefacts that are always present in radio maps (even if only below the noise) that are calibrated with incomplete sky models, as would be the case for any blind survey. While the presence of ghosts and the mechanism by which they form has been conclusively established (see recent work by Grobler, Smirnov et al.), their impact on the science performance of future deep surveys needs to be studied. Ghosts show up in specific configurations determined by the interferometer layout, and In principle affect the statistical distribution of galaxies in an image. The aim of this project is to obtain a scientific measure of how much ghosts affect the power spectrum in the intensity mapping of galaxies and to determine if they are serious enough to put a show-stopper in cosmological measurements of the galaxy distribution. The student would attempt to calibrate radio data with incomplete models and hence obtain images with ghosts and obtain a measurement of the n-point correlation functions to measure cosmological parameters. These measurements would be biased due to the presence of calibration ghosts. The magnitude of the measurements would yield information about how well calibration needs to be done (i.e. how deep the sky models need to be) in order to obtain correlations of galaxies which are not corrupted by the presence of ghosts. Other related observational techniques such as intensity mapping. this is directly relevant to SKA1 and SKA2. The results of this work will inform the calibration strategies for the next generation of deep radio surveys with JVLA,
MeerKAT and SKA1.

(PhD) TiRiFiK - better than TiRiFiC

Supervisors: Dr G. I. G. Józsa (gigjozsast@gmail.com)
Prof O. Smirnov (osmirnov@gmail.com)
Dr P. Kamphuis (peterkamphuisastronomy@gmail.com)

Prof K. Spekkens (Kristine.Spekkens@rmc.ca)

In this project, the student will participate in the (re-)development of an astronomical toolkit to simulate spatially resolved spectroscopic observations of neutral hydrogen (HI) in galaxies. The simulations are based on an extension of the tilted-ring model for galactic disks. In addition, a set of methods to automatically adjust the model parameters to optimally fit the simulation to existing observations will be investigated. Finally, both a graphical user interface for interactive work will be developed, as well as an automated heavy-duty analysis pipeline for use in large volume galaxy surveys.
While pilot studies have demonstrated the success of the technique, the challenge is to create a comprehensive, flexible, and fast set of software components that can be combined quickly by any user at a high level. One goal is to optimally serve a large number of use cases, already providing the most important application, the automated parametrisation of large-survey data. At the same time, shortcomings of existing software packages will be addressed, and the scope of existing software will be widened, including additional and alternative parametrisations.

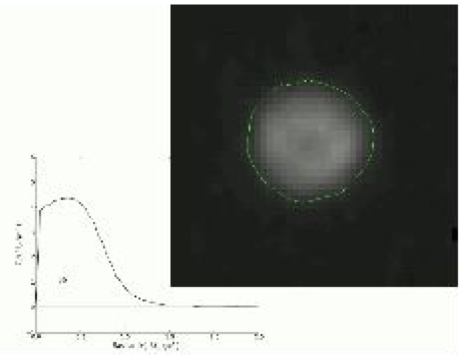
The basic concept has been investigated and prototype software is available (TiRiFiC/FAT, 3D-BAROLO). Briefly, a galactic disk is simulated according to the (tilted-ring) input parameters, projected onto a 3d spectroscopic data cube, artificially observed via a convolution, and the result compared to an input data cube to return a goodness-of-fit measure. This procedure is repeated with the goal of changing the parametrisation to optimally fit the observation.

TiRiFiK aims at an improved implementation of this concept. The toolkit will consist of low- and high level modules (e.g. written in C and Python) that can be accessed as objects of a higher-level language (Python), all accessible to the average astronomer.

(MSc) 3d stacking of neutral hydrogen in galaxies

Supervisors: Dr G. I. G. Józsa (gigjozsast@gmail.com)
Prof O. Smirnov (osmirnov@gmail.com)

We will investigate the possibility to stack (add) spatially resolved neutral-hydrogen (HI) line profiles of galaxies, as observed with radio interferometers, to enhance the average signal.



Averaged profile of 56 suitable galaxies in the WHISP survey, pilot study by Johansson et al.

Stacking techniques make it possible to study average galaxy properties to much greater depth than an individual observation would allow. Coherently adding (one-dimensional) line profiles of individual galaxies is a well-tested method, but here, we want to go a step further. By averaging the signal of resolved targets to normalised radial profiles (e.g. column density profile and rotation curve), and adding the individual observations, their (average) gas physics can be explored to much lower HI column densities.

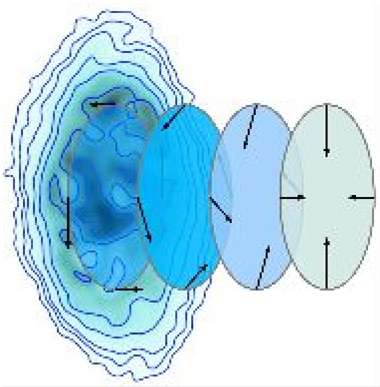
At least two questions fundamental to galaxy evolution theory and cosmology may be approached when analysing H I in emission in the reachable low-column-density regime: do spiral galaxies show a photo-ionisation edge in their HI component and what is the average slope of the rotation curve in the outskirts of galaxies?

One-dimensional stacking only relies on accurate estimates of the positions and central (redshifted) line frequencies of (point-) sources (e.g. from optical catalogues). For resolved stacking, not only one point in x-y-velocity space has to be predicted, but the complete shape. To do so, we use modern 3d fitting software (the in-house development TiRiFiC, and an automated wrapper around TiRiFiC, FAT, or their alternative, 3dBarolo) that will be applied to reconstruct the well-detectable part of the target galaxies to then extrapolate it to larger radii.

Since the method is potentially sensitive to observational- and data reduction biases, we will test it using simulated observations of galaxies. After hence exploring the limitations of the method, we will apply it on existent data sets (WHISP, Bluedisk, and others) and start preparing the automated exploit of large HI galaxy surveys.

(PhD) The vertical gaseous structure of dwarf galaxies

Supervisors: Dr G. I. G. Józsa (gigjozsast@gmail.com)
Prof O. Smirnov (osmirnov@gmail.com)
Prof C. Carignan (osmirnov@gmail.com)



Vertical structure of the dwarf galaxy UGCA 105, as found by Schmidt et al. 2014, using TiRiFiC

The project aims at the characterisation of the vertical distribution and the velocity structure of the neutral hydrogen in a sample of 3-10 selected gas-rich dwarf galaxies.

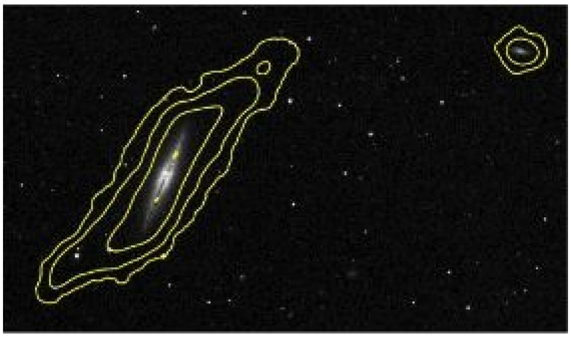
The baryonic gravitational potential of dwarf galaxies is shallow, such that, compared to their radial extent, gas-rich dwarfs are vertically more extended than spiral galaxies. At a given angular scale, their vertical velocity structure can hence be resolved and studied in detail. The proposed study, in the generalised approach as outlined below, is only possible using our own software TiRiFiC and it is hence unlikely that there will be a major conflict with concurring programs.

Two main questions will be addressed, in a detailed case-study.

Firstly, is there a significant change of the gas motion with height above the plane, which allows to infer the presence of regular gas accretion or bulk ejection? Such a detection and quantification can be used to constrain galaxy evolution models, e.g., in theory, towards lower galaxy masses, direct accretion of cold gas is not expected to happen. A frequent observation of such a phenomena in dwarf irregular galaxies would hence stand in contrast to standard galaxy formation theories.

Secondly, how do studies to determine the mass composition of dwarf galaxies, including Dark Matter, change if information about the three-dimensional structure of dwarf galaxies is taken into account? In its simplest form, this is equivalent to the question of how the derived mid-plane rotation curve changes using a 3D approach to parametrise galaxy kinematics, as employed using our software TiRiFiC, instead of a commonly applied 2D approach. A pilot study using observations of the dwarf galaxy UGCA 105 shows that the rotation curve, and hence the derived DM-halo shape, changes significantly using the 3d approach. Intrinsic and external spin alignment of disk galaxies - a pilot study

(MSc) Intrinsic and external spin alignment of disk galaxies - a pilot study



The spiral galaxy NGC 4013, optical DSS image overlaid with HI contours. The spin axis of the galaxy changes with increasing radius, it shows a typical "warp".

Supervisors: Dr G. I. G. Józsa (gigjozsast@gmail.com)
Prof O. Smirnov (osmirnov@gmail.com)
Dr P. Kamphuis (peterkamphuisastronomy@gmail.com)

In this pilot study, the spin orientation of the neutral hydrogen (HI) disks of a sample of gas-rich galaxies will be determined using interferometric spectroscopy and 3d tilted-ring modelling. The goal is to develop the technical ability to search for systematics in the HI spin alignment.

Disk galaxies acquire their star forming material continuously. Larger galaxies appear to grow inside-out with the largest-angular-momentum material being accreted most recently. Observations suggest that direct accretion of cool gas along cosmic filaments, settling at larger and larger radii, probably plays a significant role in the gas budget of galaxies. If this mechnism is indeed dominant, one would expect a preferred orientation of the spin vector at large radii, pointing into cosmic voids. However, torquing by the inner galactic disks, by interacting galaxies, by the Dark Matter halo, by winds, etc. might wash out this effect.

One would hence naively expect that the outer disks of galaxies would be better aligned with the cosmic structure than is already observed for the inner, stellar component of galaxies.

Galaxy disks are expected - and commonly observed - to be bent, or "warped". The effect of outer disks of galaxies preferrably bending with their angular momentum vector pointing into cosmic voids has been investigated using optical data, and cannot be excluded. However, since warps become most prominent beyond the bright optical disks and can be much better quantified using spectroscopy (tilted-ring modelling), future HI surveys with the SKA and its progenitors will mean a quantum leap for this kind of study.

This study will make use of small surveys (WHISP and Bluedisk), and a detection of the described effect cannot be guaranteed. But it will provide an invaluable input to this or similar future analyses of HI surveys.

(PhD) Gravitationally lensed HI with MeerKAT and the SKA

Supervisors: Dr Roger Deane (r.deane@ru.ac.za)
Dr Ian Heywood (ian.heywood@csiro.au)

Strong gravitational lensing provides the deepest views of the Universe through its magnification of the solid angle of distant galaxies combined with the conservation of surface brightness. It enables studies of high-redshift galaxies only possible with next-generation facilities without the lensing phenomenon. To date, HI has only been detected directly out to redshifts of ~0.2, limited by the sensitivity and frequency range of current radio telescopes. MeerKAT and SKA1-MID will dramatically change this picture, pushing out to redshifts of z~1 for the several thousand hour surveys proposed.

However, what has not been considered in the MeerKAT science case, is the ability to detect gravitationally lensed HI emission in high-redshift galaxies. The instantaneous bandwidth and sensitivity of MeerKAT will yield the potential to produce high-impact early science. In our recently published MNRAS Letter (Deane, Obreschkow & Heywood, 2015), we demonstrate that SKA precursors have the potential to make the highest redshift HI detections to date within a fraction of the total duration of the deep HI surveys, provided the appropriate targeted lensed surveys are designed.

The primary objectives of this PhD project are fourfold:

1) design and optimise a MeerKAT lensing survey on known lensed systems

2) use current instruments (including MeerKAT-16/32) to make the highest redshift HI detections to date

3) use our large-scale HI simulation (SAX-Lens) in combination with machine learning techniques to determine source prioritisation best practices for multi-wavelength followup of the expected >10,000 lens candidates in SKA1-MID surveys

4) investigate the ability of SKA1-LOW to detect the highest redshift HI galaxies

This ambitious programme is enabled by the significant hardware and software successes within the MeerKAT programme and Rhodes University, providing an opportunity to lead this scientific field into the SKA era.

(MSc) Disentangling supermassive black hole jets, binaries and shadows with cutting edge interferometric source modelling

Supervisors: Dr Roger Deane (r.deane@ru.ac.za)
Prof Oleg Smirnov (osmirnov@gmail.com)

Very Long Baseline Interferometry (VLBI) is the technique of combining radio signals from antennas separated by thousands of kilometres to achieve the highest angular resolution in astronomy. This enables VLBI to address many scientific questions not possible with any other type of telescope. This is particularly true of a number of observational objectives relating to supermassive black holes.

VLBI is entering into a new era enabled by hardware upgrades, correlation innovation for wide-field processing; and advances in calibration and imaging algorithms. The confluence of these factors will soon lead to large-scale VLBI surveys that increase the number of catalogued sources by orders of magnitude. In addition to wide-field, extragalactic survey-driven VLBI research programmes, a very focused experiment known as the Event Horizon Telescope (EHT, www.eventhorizontelescope.org) is in development with the goal of imaging the silhouette of the black hole at the centre of our Galaxy. These two areas both require accurate, robust source characterisation in order to extract the maximum scientific return on investment. Moreover, they require this to be performed over long time baselines as well. This M.Sc project will use cutting-edge Bayesian, compressed sensing and machine learning methods in order to make robust inferences from VLBI data, however, with direct application to a wide range of interferometric cases.

The project will focus on the robust measurement of three particular cases:

a) a black hole silhouette feature as expected from EHT observations
b) a pair of orbiting black holes over a time scale of years
c) jet precession caused by a binary black hole.

The project will leverage heavily off a wide range of sophisticated interferometric software packages developed at Rhodes University, including MeqTrees, RODRIGUES and MeqSillhouette. The project is therefore ideally suited to the student interested in black hole astrophysics and sophisticated algorithm development.

(PhD) Unveiling the Epoch of Reionization with HERA

Supervisors: Dr. Gianni Bernardi (giannibernardi75@gmail.com)
Prof. Mario Santos (mgrsantos@gmail.com)

Our current understanding of the cosmic evolution from the epoch of Hydrogen recombination (300000 years after the Big Bang) till the first billion years is very poorly known from an observational perspective, although it must have seen the growth of the initial density perturbations via gravitational attraction into the first stars and galaxies.
The 21cm transition from neutral Hydrogen promises to be the best observational probe of such cosmic time and has driven the construction of the new generation of low frequency radio arrays. The HI Epoch of Reionization Array (HERA) is the next generation of such low frequency arrays and is a partnership between several US, UK and South African institutions. The first 19 HERA dishes are currently under construction in the Karoo radio astronomy reserve and will be operational in September 2015. HERA will eventually feature 331 dishes by 2017, becoming the most sensitive 21cm telescope in the pre-SKA era.
We are seeking for an ambitious PhD candidate who is willing to become an observational 21cm cosmologist and is ready to face the many challenges that such field presents. The candidate will be able to contribute to the actual deployment of HERA and to participate in the HERA commissioning activities as well as data analysis of HERA towards measurements of the 21cm signal. In particular, the candidate is expected to work on the crucial topic of
foreground subtraction and 21cm power spectrum estimation. As HERA is a collaborative effort, the candidate is expected to work together with the US and UK partners.
An ideal candidate will have a good background in physics and mathematics, the willingness to learn about advanced radio interferometry, statistics, signal processing techniques and cosmology, but, mostly, the desire to contribute to the 21cm cosmology revolution.

(MSc) Studying the thermal history of the intergalactic medium with the global 21cm signal

Supervisors: Dr. Gianni Bernardi (giannibernardi75@gmail.com)
Prof. Mario Santos (mgrsantos@gmail.com)

Our current understanding of the cosmic evolution from the epoch of Hydrogen

recombination (300000 years after the Big Bang) till the first billion years is very poorly known from an observational perspective, although it must have seen the growth of the initial density perturbations via gravitational attraction into the first stars and galaxies.
The 21cm transition from neutral Hydrogen promises to be the best observational probe of such cosmic time and has driven the construction of the new generation of low frequency radio arrays. Parallel to them, single-dipole experiments have been built to measure the all-sky 21cm spectrum: such measurement can in principle be obtained with only a few tens of hours of observing time. In principle, therefore, observations of the global 21cm signal are easier than observations of 21cm fluctuations carried out with large interferometric arrays and are very sensitive probes of the ionization and thermal history of the intergalactic medium. The biggest challenge for such observations is the subtraction of the bright Galactic foreground.
In this thesis project the candidate is expected to familiarize with the theory and the observational background of the global 21cm signal and, afterwards, apply existing algorithms to remove foregrounds and measure the underlying 21cm signal in simulated cases. In particular, the candidate will interface a Bayesian foreground subtraction algorithm (developed by the supervisor) with the 21cm simulation code Simfast21 (developed by the co-supervisor) in order to produce a realistic signal extraction pipeline. The candidate will be using such pipeline to explore the detectability of the 21cm signal for different global 21cm experiments.
An ideal candidate will have a good background in physics and mathematics, the willingness to learn about Bayesian data analysis and the desire to explore the cutting edge research field of 21cm cosmology.

(MSc or PhD) Diffuse radio emission from galaxy clusters

Supervisors: Dr. Gianni Bernardi (giannibernardi75@gmail.com)
Prof. Oleg Smirnov (osmirnov@gmail.com)

Galaxy clusters are the largest gravitationally bound structures and emit electromagnetic radiation at almost all wavelength. In particular, some of them, host diffuse, Mpc scale, low brightness sensitivity radio sources that have been the subject of intense investigation over the last two decades. Developments in recent observations and theoretical models suggest that such structures are created by merging events, when magnetic fields are amplified and particles re-accelerated to relativistic energies but additional observations are required to further test models.
The candidate will have the opportunity to work on WSRT observations of two clusters (A773 a/o A781) that are particularly interesting as they have been selected for their active

dynamical state. He/she will be reducing the data, carrying out the scientific analysis and interpretation of the results. Observations of diffuse emission from galaxy clusters are ideal laboratories to test advanced calibration (i.e. direction dependent calibration) and imaging techniques (the recently developed PyMORESANE) as they require a careful analysis to extract the low brightness sensitivity structures.
An ideal candidate will have the interest in developing an radio observational expertise, familiarizing/developing calibration and imaging pipelines and the desire to work on a prominent field (galaxy clusters) that will be relevant for MeerKAT observations.