South African Radio Astronomy Observatory
Research Project Proposals for Masters and Doctoral Research in 2020

Section A: Overview of the Research Project Proposal

1. **Academic level:** Masters
2. **Field of research:** Astronomy / Astrophysics
3. **Title:** HI Imaging of the Norma Cluster with MeerKAT
4. **Supervisor and co-supervisor:** Mpati Ramatsoku and Oleg Smirnov
5. **University:** Rhodes University

Abstract
Galaxies are mostly a composition of gas and stars. Interactions that occur between these two components cause galaxies to evolve with time. During this evolution galaxies ultimately deplete all of their star-forming fuel in the form of cold and dense gas. Understanding precisely when this happens is not as simple as dividing the amount of gas present in a galaxy by the rate at which stars are formed. There is a multitude of processes that can deplete gas from a galaxy or even stop gas from cooling and condensing to form stars. Although we have a good "grasp" on which processes might deplete gas or stop star-formation, there are still unanswered questions, such as where these processes occur? how do they work in a given galaxy with a certain mass? when they occur and which process has the most dominant effect? Through observations, it is clear that the galaxy cluster environment, with its high density of galaxies, has a profound impact on the evolution of galaxies. Numerous studies of the cold neutral atomic gas (HI) have also shown the importance of having a HI perspective when examining the cluster environmental effects on galaxy evolution because of the sensitive nature of this gas phase to the harsh cluster environments. However, pieces of the puzzle are still missing due to some degree, the limitations imposed by previous radio instruments. This project will exploit the higher sensitivity of the MeerKAT telescope to study the HI properties of galaxies within the dynamic and harsh Norma cluster and its influence on the galaxies' star formation activity.

Section B: Research Project Proposal

1. Scientific merit

Critical cosmological probes such as galaxy clusters have shaped much of our current understanding of galaxy formation and evolution (Vikhlinin+ 2009, Mantz+ 2010, Bell+ 2004, Miller+ 2009). Nearby galaxy clusters have particularly been instrumental in this because we are able to study them at a level of detail that would not be possible for clusters at higher redshifts (eg., Drinkwater+ 2001, Chung+ 2009, Karachentsev+ 2014, Weinzirl+ 2014). By studying nearby clusters it has been shown that galaxies start out as late-type and gas-rich in the field and by the time they reach cluster cores they have been transformed into gas-poor early-type galaxies; i.e., the morphology-density relation (Dressler, 1980). Since galaxies are, in their observable constituents, systems of gas and stars, this relation indicates that, in dense cluster environments, they tend to rapidly lose their gas which stops the formation of new stars. On the other hand, in low-density environments, galaxies are able to retain their gas and even accrete more gas, effectively providing fuel for star formation. By understanding the complex relationship between galaxies and their environments important information on the processes responsible for galaxy evolution can be attained.

For example, we already know of some environment-specific mechanisms responsible for the evolution of galaxies particularly in galaxy clusters. Some of these affect both the stellar and gaseous components of galaxies such as mergers, where galaxies collide with each other at relatively low velocities thus leading to the removal of gas as it becomes gravitationally detached during the collision (Toomre+ 1972, Walker+ 1996). Other mechanisms such as harassment occur when galaxies interact gravitationally along their orbits as they transition into the cluster cores. This consequently perturbs the gas and stellar distribution. In instances where harassment is sufficiently severe, the majority of the gas clouds will be affected and the galaxy will undergo an abrupt burst of star formation which consumes all of the fuel for new stars (Moore+ 1996, Duc+ 2008, Smith+ 2015). In less severe harassment cases only the diffuse gaseous halo is perturbed, this effectively stops the gas from cooling and condensing thus "quenching" star formation (Dressler+ 2013, Cattaneo+ 2015, Peng+ 2015, Jaffe+ 2016).

One of the more effective mechanism at transforming galaxies in clusters is ram-pressure stripping (Gunn & Gott, 1972,Kapferer+ 2009, Chung+ 2009, Abramson+ 2011, Jaffe+ 2015, Yoon+ 2017, Poggianti+ 2017). This process only affects the gas component of the galaxy and often occurs in clusters with the hot X-ray emitting gas which forms the intra-cluster medium (ICM). As a galaxy falls into the cluster core it passes through this ICM which in turn exerts hydrodynamical pressure on the galaxy. If the ICM pressure is sufficiently high, it can overpower the gravitational force keeping the gas bound to the galaxy, effectively stripping the galaxy of its star-formation fuel (Moran+ 2007, Porter+ 2008, Dressler+ 2013, Jaffe+ 2015).

Although we are aware of these mechanisms, their timescales are still not completely understood and some questions still remain open; for example on the exact origin of the non-star forming galaxies in the centres of galaxy clusters. Could gas removal mechanisms such as galaxy mergers and harassment be sufficiently effective at completely removing gas from the infalling groups of galaxies or is ram-pressure stripping acting alone at creating this population? While some studies on this matter have presented evidence indicating that indeed some galaxy "pre-processing" does occur to a certain degree in galaxies before falling into the cluster core, the relevance of this pre-processing in the formation of gas-poor non star-forming galaxies is still debated and not yet well understood (Zabludoff+ 1998, Verdes-Montenegro+ 2001, Ellingson+ 2001, De Lucia+ 2012, Hess+ 2013, McGee+ 2009, Vijayaraghavan+ 2013).

Observing emission from the neutral gas (HI) provides an opportunity to start addressing some of these questions since it is a reservoir for H2 which is an important ingredient for star-formation. Furthermore, the cluster environment leaves clear imprints on the delicate and diffuse HI-disks of galaxies, thereby making HI an ideal tool to start studying and understanding the complex processes affecting star-formation and consequently galaxy evolution (Poggianti+ 2001, Bravo-Alfaro+ 2000, Bravo-Alfaro+ 2009, Chung+ 2009, Gavazzi+ 2013, Jaffe+ 2015, Yoon+ 2017).

HI imaging of the Norma cluster with MeerKAT

The aim of this project is to make use of the aforementioned property of the HI gas to study what drives galaxy evolution in the dense cluster environment. Particularly, circumstances under which galaxies lose their fuel for star formation i.e., cold gas, and/or what stops the accretion of new gas. The Norma cluster is ideal for this study. It is a nearby galaxy cluster ~65 Mpc that is rich and massive with a dynamical mass of $M_{dyn} \sim 10^{15} M_{\odot}$. This galaxy cluster is comparable to the well-known/studied Coma cluster. However, unlike its counterpart, the Norma cluster has not yet reached a dynamically relaxed state, as revealed by the large amount of substructure indicated by its spiral and irregular galaxies. Its X-ray morphology is asymmetric — an indication of an ongoing cluster merger. Moreover, it has remained mainly unexplored due to its location at low galactic latitudes.

The goals of the HI imaging of the Norma cluster with MeerKAT are as follows:

A. **Pre-processing from an HI perspective:** Using the deep MeerKAT HI data in combination with ancillary data from e.g., WISE, the effect of galaxy pre-processing on the HI properties will be studied as a function of galaxies' location within the cluster. This is especially viable due to the highly dynamic nature of the Norma cluster.

B. **Search for HI tails:** The spatially resolved HI detections will provide means to quantitatively characterise and study the detailed morphologies of HI in galaxies as a function of their distance from the cluster centre. This will effectively provide hints on the various environment-specific mechanism acting upon the galaxies.

C. **Star formation efficiency in the harsh Norma cluster environment:** The relation between neutral gas content and the stellar populations in the Norma cluster will be used to investigate the star formation efficiency under the harsh environmental mechanism of ram-pressure stripping from the ICM of this cluster. Essentially we will investigate the star formation rate enhancement/quenching and its connection to HI consumption timescale in this galaxy cluster

2. Feasibility

The HI data required for this project have already been observed and are currently available and it is of sufficient quality for this study. A large portion of the analysis for this project depends on ancillary multi-wavelength data. These complimentary data are available; optical redshifts for galaxy cluster members will be extracted from the published 2dF spectroscopy catalogue of Woudt+ 2008. The stellar distribution of the galaxies in the galaxy cluster will be obtained from the Ks-band of the 2MASS Extended Sources Survey because extinction at optical wavelengths at these low galactic latitudes is severe. Additionally, stellar masses for the individual galaxies will be gathered from the 3.4μm (W3) WISE band. Therefore, all data required to undertake this study are available or obtainable.

A plausible time-frame for the project is as follows:

Year 0 - 0.5: Literature review to be conducted by the student covering observational radio astronomy and interferometry. This time will also be used by the student to understand the topic and to become up to date with the latest scientific results on the subject, and become familiar with the scientific goals of the project as well as the scientific questions to be addressed in the master's dissertation.

Year 1 - 1.5: The student is expected to perform source-finding to search for all the HI detected galaxies. This process will also include collecting and processing all the complementary multi-wavelength data required. In addition analyses required to start addressing the scientific questions as outlined will also be conducted during this time.

Year 1.5 - 2: The student will finalise results and write up the thesis. A paper is expected to follow based on the results of this project.

Key discussions / results / plots expected from the student:

To address questions outlined in the project description, the student will be expected to conduct some key discussions and make some main plots including but not limited to;

- a plot showing the position of Norma galaxies relative to standard scaling relations. This is important to examine how much of the gas content of these galaxies has been removed by environmental mechanisms in this cluster.

- an illustration and discussion of the HI properties such as deficiencies, morphologies, masses, etc., as a function of the position of galaxies in the cluster. This would also include a spatial distribution plot of the detected galaxies, and a deep discussion of the position of galaxies in the 3D projected phase-space diagram to analyse the galaxy gas stripping sequence in this space.

- a plot showing the star-formation properties relative to the HI content to probe the relative timescale of gas removal and star-formation activity. a plot identifying the various substructures/infalling groups with an analysis of their HI content and distribution. This is to be used in the search for evidence of pre-processing of the gas content of the galaxies groups within the Norma cluster.

3. SARAO research priority areas

- Science topics that involve the exploitation of MeerKAT data project already available in 2019.

4. Requirements of candidates

For this project, a candidate would require an undergraduate degree in astronomy, physics, engineering or similar discipline. Working knowledge of Linux operating systems and the Python/Matlab or any other programming language is desirable, and if not present the candidate must be capable of becoming rapidly familiar with the programming languages needed.