Section A: Overview of the Research Project Proposal

1. Academic level:	MSc
2. Broad field of research:	Astronomy/Astrophysics
3. Title of the research project:	A MeerKAT HI and radio continuum study of the archetype binary AGN host galaxy NGC 6240
4. Supervisor:	Prof Roger P. Deane
5. Institution:	University of Pretoria

Section B: Research Project Proposal

1. **Scientific merit:** *describe the objectives of the research project, placing them in the context of the current key questions and understanding of the field.*

This MSc project is an HI emission, absorption, and radio continuum study of a prototypical binary AGN system, NGC 6240. This well-studied galaxy is an excellent example of radiative and mechanical feedback, with a high star formation rate, prominent outflows, and a bright associated radio source. It is very nearby in the Universe (~100 Mpc) enabling a detailed analysis at MeerKAT's ~10 arcsec angular resolution. The primary objective is map out diffuse radio continuum and the disrupted HI disk and relate this to the previously studied ionised gas dynamics. Insights gained from this nearby Universe study may provide useful information in identifying comparable systems at higher redshifts as probed by MeerKAT Large Survey Projects coupled with future wide-field OIR spectroscopic surveys.

Dual or binary supermassive black hole (SMBH) systems have long been predicted to be common in the Universe (Begelman, Blandford & Rees, 1980), the expected combined result of (a) hierarchical galaxy formation (e.g. Springel et al., 2005), and (b) all massive galaxies hosting a nuclear black hole (Kormendy & Richstone 1995). Their primary importance stems from the expectation that sub-parsec binary SMBHs dominate the stochastic gravitational wave background at nHz-μHz frequencies (Wyithe & Loeb 2003, Sesana 2013). However, another important consequence of these systems is on the host galaxies themselves. Hydrodynamical simulations predict significant increases in the star formation rate and AGN accretion rate as a dual/binary SMBH pair spiral in towards one another and disrupt the neutral and ionized gas angular momentum. However, there are counter examples as well, such as that shown in a recent detailed HST study of the prototypical, nearby dual AGN system that is the subject of this proposed MSc project, NGC 6240, which suggests comparable levels of positive and negative feedback (Muller-Sanchez et al. 2018). Understanding this role is an important, often overlooked ingredient in confronting observations with semi-analytic and hydrodynamical models of galaxy evolution (e.g. Crain et al. 2015). This MSc project proposes to do exactly that through a previously unexploited window on dual SMBH effects: the neutral hydrogen distribution and dynamics. Not only is this important for investigating the individual systems themselves, but given the key point that this is a confirmed, well-studied dual AGN with the nuclei positions known, these data may well assist in searching for similar systems at higher redshifts through the deep MeerKAT HI surveys of LADUMA and MIGHTEE. The combination of this detailed low-redshift study with the large-number statistics of MIGHTEE+LADUMA will likely improve our ability to discern dual AGN effects from a single AGN and/or star formation induced outflows at higher redshift. Doing so is important in understanding the relative contribution of these feedback processes, which become increasingly relevant at higher redshift.

NGC 6240 is one of the archetype dual AGN systems, first discovered by Komossa et al. (2003). Its two active, X-ray detected nuclei ($L_{bol} \sim 3\text{-}8 \times 10^{37}$ W) are separated by 0.7 kpc and embedded in a highly disturbed galaxy with a SFR > 100 $M_{\odot}$ yr^{-1}. This rather dramatic system is commonly called the 'Butterfly Nebula' due to is distorted shape. Recently, Muller-Sanchez et al. (*Nature*, 2018) performed a deep HST and VLT SINFONI analysis of this nearby system that reveals both star formation and AGN-driven outflows. These are seemingly spatially isolated, providing a remarkably clear view of these feedback processes. From this study the following conclusions are relevant to the goals of this MSc project: (1) there is a AGN-driven ionization cone in the north-eastern region which is spatially uncorrelated with the stellar continuum or molecular gas disk, similar to that seen in Seyfert IIs; (2) the molecular (H_2) gas, as traced by SINFONI, reveals a large, perturbed rotating disk ($v_{rot} \sim 220$ km s^{-1}) that is not aligned with the projected orbital plane of the dual AGN, (3) extra-planar regions of Hα bubbles and filaments are observed in the north-west and south-east, which are likely driven by stellar winds, (4) overall, the AGN and star formation outflows are estimated to be driving 75 and 10 $M_{\odot}$ yr^{-1} out of NGC 6240 respectively, which is comparable to the inferred SFR and indicates an crucial phase in this galaxy's evolution.

Two important aspects are missing from this picture and this MSc project aims to provide both: (1) the neutral gas distribution and dynamics to determine how the two outflows have affected this and a more complete estimate of total outflow rate; and (2) mapping the radio continuum to determine if mechanical feedback is playing an important role or if most of the ~0.5 Jy flux is concentrated in the two nuclei. This is therefore a prime case study for MeerKAT in probing feedback processes, leveraging off a wealth of exquisite HST, VLT, and Chandra data.

2. Feasibility: ***outline the methods that will be used to achieve the objectives. Provide details on the availability of required data / access to required equipment / availability of research facilities and other resources required. Include any relevant expected intermediate milestones and associated timeframes towards attaining the overall objectives of the project.***

Calibration and imaging of MeerKAT datasets is a computationally expensive process, however, the University of Pretoria is extremely well equipped to perform this, by virtue of its membership to the Inter-University Institute for Data-Intensive Astronomy (IDIA).

Calibration and imaging of datasets using the exact same correlation mode have been successful, so no exception is expected here. Note the the project is not critically reliant on HI detection, even though this is expected, since the radio continuum analysis will be compelling enough for an MSc project, given the extreme interest in this object (e.g. the 2018 *Nature* paper dedicated ionised gas dynamics within it).

All required MeerKAT data for this project is in hand.

3. **Link the proposed project to one or more of the SARAO research priority areas for 2020** *(refer to Section 4 of the Application Guide), and explain in some detail how the proposed research will contribute to the priority area(s).*

This project of course relates directly to Science topics with MeerKAT, playing a complementary role to a number of MeerKAT Large Survey Projects that aim to decouple the relative importance of AGN activity and star formation in driving galaxy evolution.

4. If relevant, describe any particular qualifications, academic abilities, skills and/or experience that a student should have in order to successfully deliver on the objectives of the research proposed.

Some experience with interferometric calibration and imaging will be beneficial but not essential.