Details for research project

Section A

1. **Title:** A pilot survey for a MeerKAT HI census of Local Volume galaxies
2. **Broad area of research:** Science
3. **Academic level:** Doctoral
4. **Abstract of research project:**

Galaxies within a sphere (centred on Earth) of ~ 11 Mpc are said to be part of the Local Volume (LV). To date, nearly 1000 LV galaxies have been catalogued. Many of them have had their global properties studied: luminosity, mass, distance, size. This makes them a useful sample for studying the dynamics of the local Universe. However, in order for them to be used as probes of galaxy evolution, spatially-resolved multi-wavelength studies of their properties must be undertaken. This has been done at optical and infrared wavelengths quite extensively. However, at radio wavelengths, on a small fraction have been targeted with an interferometer. For the rest, we know very little about the distribution and kinematics of their dominant gas component.

This project aims to serve as a pilot study of a potentially large survey that could be carried out with MeerKAT. Spatially resolving the HI content of a statistically significant fraction of the LV galaxies will allow us to study their fundamental properties (rotation, dark matter) effectively and accurately, thereby opening up a new window for the study of our nearest neighbours.

5. **Primary supervisor details:**
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    - **c. University:** University of the Western Cape

Section B

Scientific merit:

In terms of numbers, the Local Volume (LV) is made up largely of small, dwarf galaxies. These galaxies are sensitive probes of cosmology. They do, in fact, constitute the most representative sample of galaxies we have, and allow us to test various cosmological paradigms. In recent years, discrepancies have been noted between theoretically (computationally) predicted dwarf galaxy counts and counts based on observational data. Properly resolving the issue will offer important insights into the behaviour of our Universe on large and small scales.

On their own, dwarf galaxies are very interesting systems. Again, in recent years, many a debate has arisen regarding the distribution of dark matter within these galaxies. Observers claim them to have a roughly constant density core, whereas theorists claim their cores to be cuspy. Although this problem is now largely alleviated (thanks to the proper modelling of baryonic processes), there's no doubt that we still have much to learn about the important galaxies.

To date, fewer than 100 LV galaxies have been observed with an interferometer. Koribalski et al. (2018) presented (as part of the LVHIS survey) ATACA imaging for 82 LV galaxies that were detected by HIPASS. The sample, however, was biased towards LV galaxies with larger HI masses. Being based on ATACA in configurations extending up to 1.5 km, the LVHIS imaging is of modest spatial resolution, typically peaking at ~ 40 arcsec.

Clearly, what we are still lacking is a systematic HI interferometric survey of a larger fraction of the LV galaxies, specifically those with low stellar mass. These are the most typical galaxies in the Universe, yet we've not yet begun studying them in rigorous detail. This PhD project aims to address this problem by serving as a pilot study for a long-term MeerKAT survey that will observe many LV galaxies in HI line emission. High-quality HI data (that spatially resolved the galaxies) supplemented with other multi-wavelength imaging will yield a formidable data set that can be used to study the properties of LV galaxies.

We do, in fact, have several hundreds of dwarf galaxies in our own backyard, many of which have been observed at various wavelengths. The Nearby Galaxy Catalogue (NGC) from Karachentsev et al. (2013) lists important global properties for 869 galaxies: luminosities, sizes, masses, distances. Shown in Fig. 1 is the sky distribution of these NGC galaxies. The NGC catalogue is a valuable resource, yet the ways in which it can be used to study galaxy evolution (for example: the baryon cycle in galaxies) is limited due to the nature of the data making up the catalogue. Very few LV galaxies have been observed in detail, and even fewer have been spatially resolved in HI.

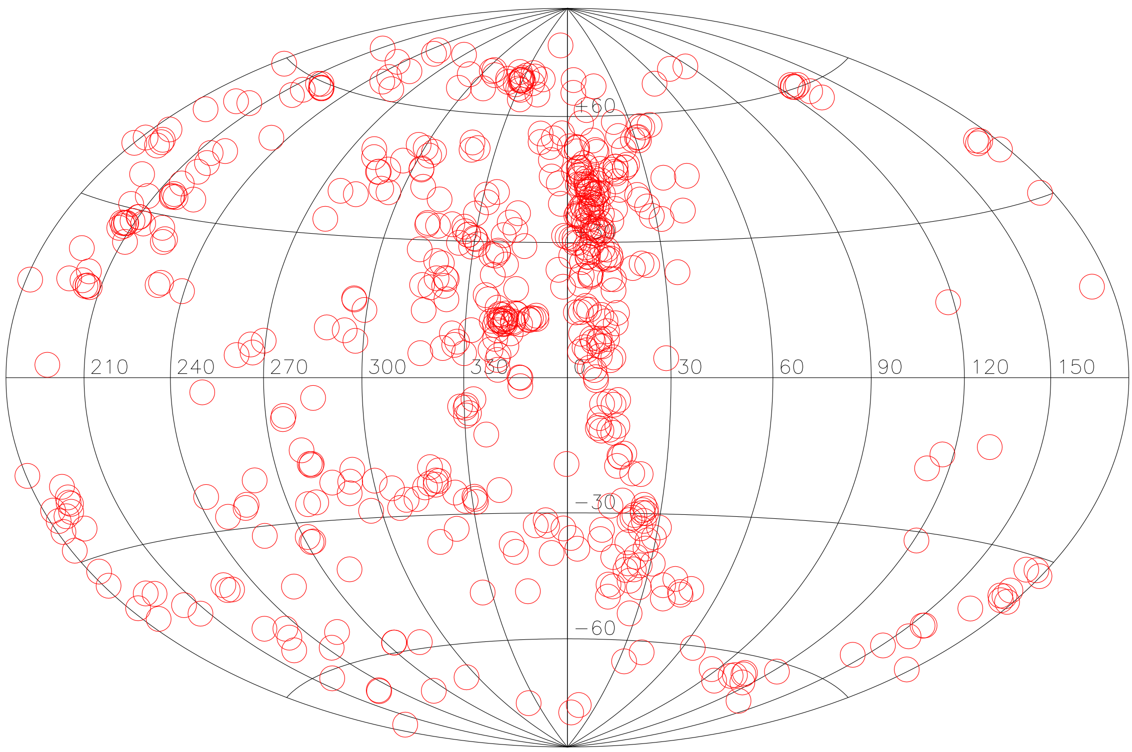

Figure 1: *Distribution of 869 galaxies presented in the Karachentsev Nearby Galaxy Catalogue. Many of these can be easily observed with MeerKAT to probe the details of their HI content.*

Out of the 869 galaxies in the NGC, 291 of them lie south of Declination=+30 deg. Many of these galaxies should be accessible to MeerKAT, and their HI content could be very well detected with short on-source integration times. For this project, the PhD candidate will focus on studying a small subset of galaxies (possibly 20 to 30) with MeerKAT, thereby generating a primary data set for the PhD consisting of high-quality HI line observations. These data will be supplemented with infrared (and possibly optical) imaging from other South African facilities. Combined, the data will allow us to probe the internal distributions and kinematics for a statistically-significant sample of LV galaxies.

Feasibility:

HI data:
Ideally, the MeerKAT data should be acquired before the candidate starts their work in 2021. An open time call for 32k correlator mode observations with MeerKAT in 2020 is keenly anticipated. When it arrives, a proposal will be submitted to observe the 20 - 30 most promising LV galaxies with MeerKAT. If the data cannot be acquired in 2020, efforts will be made to acquire them in 2021 as part of the early stages of the PhD.

All of the LV galaxies in the NGC should be easily detected with an instrument as powerful as MeerKAT. This claim is supported by the data shown in Fig. 2. In all panels, blue bins represent the full NGC, while red bins represent the 291 galaxies with Dec < +30 deg that should be accessible to MeerKAT. Panel a shows the Ks-band magnitudes of the galaxies, panel b the distances. The galaxy HI masses are shown in panel c. For comparison, HI masses for the 82 LVHIS galaxies are shown as the green bins. Combining the distances and masses yields the integrated flux densities shown in panel d. Clearly, even though most of these galaxies have small HI masses, their proximity to Earth makes them very bright in HI line emission. For reference, the average integrated HI flux density of the THINGS galaxies is 278 Jy km/s. The THINGS galaxies are represented by the green bins in panel d. Panel e shows the HI line widths of the galaxies. Panels d and e yield panel f - the average HI flux density in a channel of width 10 km/s (47 kHz). Clearly, even in a single channel, all of the galaxies contain a lot of HI flux. These values can be compared to the noise curve shown in panel g. This curve was generated assuming SEFD=450 Jy @ 1420 MHz and df=47 kHz. The curve actually show 5 times the theoretical noise RMS in a single 10 km/s channel. Clearly, all NGC galaxies should be easily detected by MeerKAT with very short integration times. To ensure truly deep, exquisite observations, each galaxy can be observed for an hour. The excellent snapshot capabilities of MeerKAT will ensure that such short integration times yield good uv coverage, which in turn will yield neat PSFs.

Infrared data:
Infrared observations of the galaxies are crucial for the sake of measuring the properties of their old stellar populations. Measures of their HI and stellar content is needed to generate mass models that constrain their dark matter properties. The LV galaxies have indeed been observed as part of all-sky surveys carried out from the ground and from space. However, the imaging from such surveys is typically quite shallow. Kirby et al. (2008) show that due to the shallowness of the 2MASS photometry, fluxes of detected galaxies may be underestimated by up to 70 per cent. Young et al. (2014) present deep H-band observations of 40 LV galaxies. They demonstrate that deep targeted surveys are the most reliable means of obtaining accurate surface photometry. Furthermore, they show that the significantly varied colours of dwarf galaxies eliminate the possibility of using optical-near infrared colour transformations to facilitate comparison to more widely available optical data sets.

It is for these reasons that the PhD candidate will be tasked with acquiring new infrared imaging for the LV galaxies, using the 1.4 m Infrared Survey Facility (IRSF) in Sutherland. This will yield deep infrared imaging with seeing-limited resolution (~ 1.5 arcsec). This will be a significant improvement on existing data from all-sky surveys, and will complement the HI imaging to offer the possibility of generating very accurate mass models for the galaxies. The PI of this proposal has already initiated a campaign to observe LV galaxies with the IRSF. Indeed, preliminary results suggest that high-quality imaging is attainable. The PI will guide the student through the data reduction process. In the case that the HI cubes are not available at the start of the PhD, the student will be tasked with first acquiring the IR data.

Spatially-resolved HI studies:
The main aim of this project is to generate and analyse *spatially-resolved* HI imaging of LV galaxies. This will allow for rotation curves to be produced, HI distributions to be quantified, and small-scale star formation processes to be studied. While many of the LV galaxies have been observed in HI, this has been mostly using single-dish radio telescopes. Therefore, we have only global HI spectra for >90% of the galaxies, not spatially-resolved imaging. Although the HI sizes of the galaxies are currently unknown, the resolving power of MeerKAT will allow for spatially-resolved studies to be carried out. Obreschkow et al. (2009) provide a simple relation between the HI mass of a galaxy and its HI radius. Using it, we can estimate the HI diameters of the NGC

galaxies - these are shown in panel g of Fig. 2. Clearly, the angular diameters of the NGC galaxies are all large - much larger than the typical spatial resolution (~ 15 arcsec) of a naturally-weighted MeerKAT HI cube. *The galaxies will therefore be spatially resolved*. This will allow for the spatially resolved dynamics of the galaxies (i.e., velocity fields and rotation curves) to be studied. In turn, this will yield mass models for the galaxies that will constrain their dark matter properties. The PI of this proposal is extensively experienced in the methods of generating rotation curves and mass models from multi-wavelength image sets, and will be able to guide the student in these efforts.

Data processing:
All data processing will be carried out using the IDIA resources. Being based at UWC, the student will have access to the full suite of IDIA-based software. This includes the ProcessMeerKAT pipeline that will be used reduce the uv data. The PI of this proposal has already successfully used ProcessMeerKAT to reduce uv data for a nearby galaxy pair, observed as part of the Open Time call for MeerKAT in 4k correlator mode. Once the HI cubes for this PhD project have been generated, they will be used to generate further data products using bespoke Python scripts. Analysis of these HI products will be carried out using standard packages (GIPSY, BBAROLO). Infrared imaging from IRSF will be reduced using an existing pipeline dedicated to the handling of IRSF data. Modest computational resources (e.g., a laptop) will be required to do this.

Time frames:
As mentioned above, *it will be most ideal to acquire the HI imaging for this PhD in 2020*, as part of the next MeerKAT Open Time Call. If that goal is achieved, the student can spend the first 6 months of the PhD using ProcessMeerKAT to produce HI data cubes and associated HI data products. At the same time, the student can obtain new infrared imaging of the galaxies using the IRSF in Sutherland. A single IRSF observing run of ~ 2 weeks all be enough to acquire all the IR imaging. Thereafter, the student can use the dedicated pipeline to reduce the imaging.

The second year of the project will focus on the analysis. Dynamical models will be fit to the HI data in order to generate rotation curves. The infrared imaging will be incorporated to extract detailed mass models from the rotation curves. Other HI structural properties will also be investigated: HI morphologies, mass profiles, etc. An attempt will be made to link the HI properties of the galaxies to their star formation properties. While the IRSF imaging alone will not yield star formation measures, global measures will be available from WISE imaging (which the PI has access to).

The last year of the PhD will focus on wrapping up the data analysis components and writing up the thesis.

Links to SARAO research priorities:

The main goals of this project are clearly linked to SARAO efforts aimed at using MeerKAT to carry out detailed studies of the galaxies. In fact, many of the goals and methods of this PhD will be very similar to those of the MHONGOOSE survey, albeit with a very different galaxy sample.

Required student qualifications:

A competent, diligent student is needed to work on this project. The workload is expected to be high, yet appropriate enough to allow for a good work/life balance. The student will certainly need to work at least 40 hours a week on the project. The student must be experienced in working with real galaxy imaging - this is not a pen and paper theoretical project. The successful applicant should have some good experience with handling HI data cubes and other multi-wavelength image sets of nearby galaxies. A good general understanding of galaxy evolution is necessary. Good Python programming skills are required, and experience with high-performance computing facilities such as ilifu will be beneficial. Because there will be many data sets to work with, the student must be capable of being organised and managing a moderately-sized project.

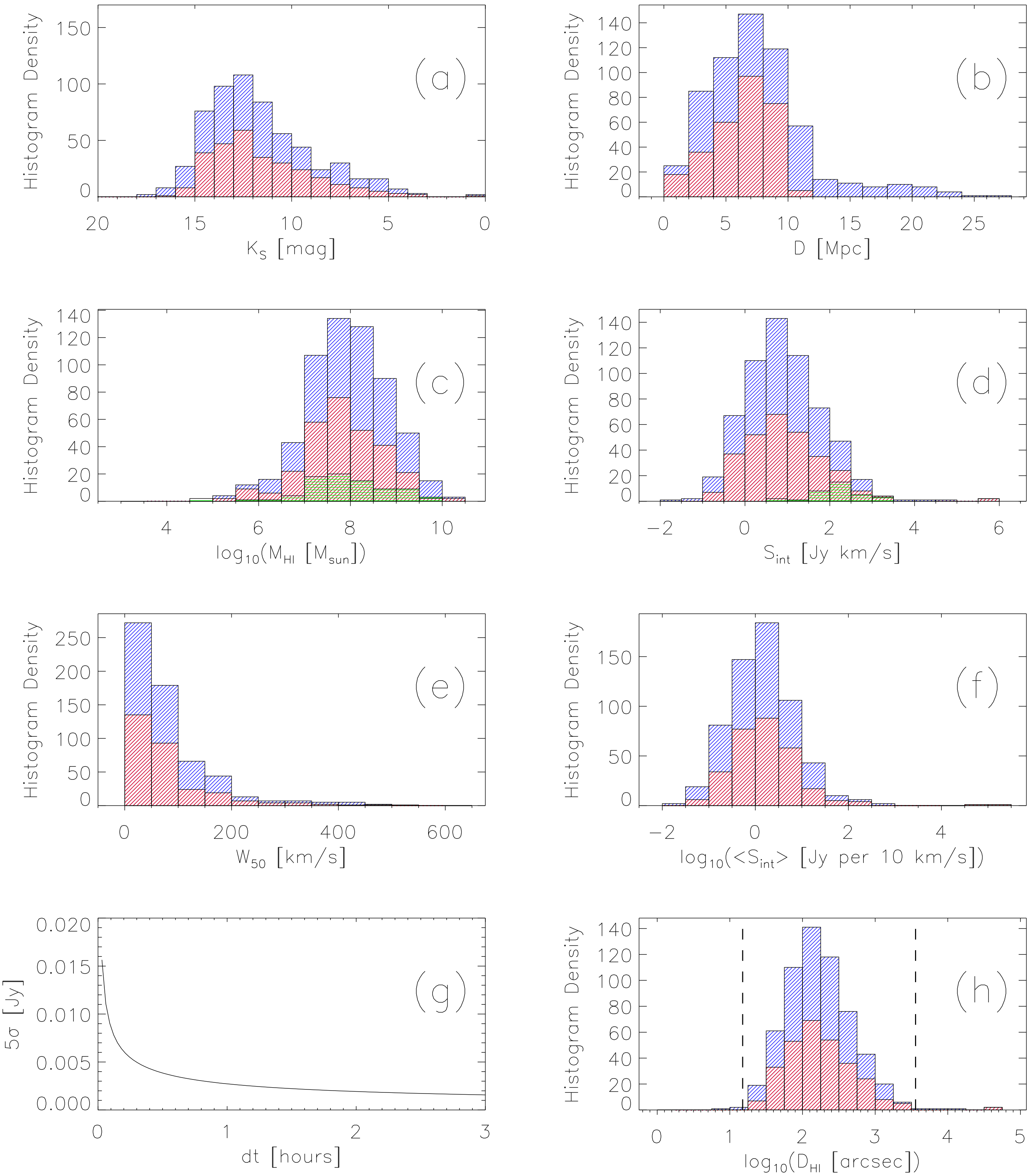

Figure 2: *Distributions of various important parameters for the full NGC catalogue (blue bins) and those 291 galaxies that should be accessible to MeerKAT (i.e., Dec < +30 deg, red bins). Panel a shows Ks-band magnitude, panel b distance. Panel c shows HI mass. Green bins represent the masses of 82 galaxies from the Local Volume HI Survey (LVHIS). This is the one survey that has systematically targeted LV galaxies with a radio interferometer. Panel d shows integrated HI flux density. Green bins represent the THINGS galaxies, for comparison. Panel e shows HI velocity width, panel f average HI flux density in a 10 km/s channel. Panel g shows the theoretical 5-sigma noise level for MeerKAT observations (assuming SEFD=450 Jy @ 1.4 GHz and df=47 kHz) as a function of time. All galaxies in the NGC should be easily detected by MeerKAT. Panel h shows the angular diameters of the galaxies. The leftmost vertical dashed line is at 15 arcsec - it represents the spatial resolution of a typical naturally-weight HI cube from MeerKAT. Clearly, all galaxies will be spatially resolved. The rightmost line is at 1 deg - it represents the approximate size of the MeerKAT field of view. Clearly, essentially all NGC galaxies will fit well within a single MeerKAT pointing.*