Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025

MeerKAT view of Hickson Compact Groups: data products and HI deficiency

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Abstract

Hickson Compact Groups (HCGs) are dense collections of 4–10 gravitationally-bound galaxies, making them excellent laboratories for exploring processes leading to star formation quenching. To understand how HCGs evolve from exhibiting intricate H I tidal structures in the so-called phase 2 to the near or complete depletion of H I in phase 3, we have observed three phase 2 HCGs and three phase 3 HCGs with the MeerKAT radio telescope. We also aim to search for diffuse H I gas that have been undetected in previous Very Large Array (VLA) observations but were apparent in Green Bank Telescope (GBT) spectra reported in the literature. In this contribution, we describe the observations, data reduction processes, the data products, and the H I deficiency of the groups and their surrounding galaxies. For phase 2 groups, MeerKAT uncovered much more extended H I tidal structures than previous VLA observations. For phase 3 groups, some new high surface brightness features were detected, although no diffuse H I was identified. Additionally, numerous surrounding galaxies, mostly normal disk galaxies, were detected around our observed HCGs. Our data indicates that the H I in phase 2 groups may span to even larger angular scales than currently observed. Finally, galaxies within the virial radius tend to be more deficient than those outside.

1 Introduction

Hickson Compact Groups (HCGs) are collections of four to ten closely spaced galaxies, originally catalogued by [4]. They are located in low-density environments, and have low velocity dispersions (∼200 km/s). Their galaxy separations are similar to those in cluster centers, making them valuable for studying processes that quench gas and star formation. [13] proposed an evolutionary sequence in which HCGs evolve through three main phases. In phase 1, the neutral hydrogen (H I) in HCGs are mostly confined to the galaxies' disks. In phase 2, subsequent gravitational interactions disrupt the gas distribution, leading to numerous tidal features and intragroup gas clouds. In phase 3, the groups lose almost or all of its gas content.

The H I properties of HCGs have been extensively studied in the literature. Early observations by [12] showed that their sample of 51 HCGs contain, on average, 50% less H I than expected from their optical characteristics. Additionally, [13] found that their studied HCGs have, on average, 40% of the predicted H I, with the individual galaxies having higher H I deficiency than the group as a whole. Observations with the Green Bank Telescope (GBT) by [2] identified diffuse H I extending over a large velocity range missed by previous Very Large Array (VLA) observations. The newly detected diffuse H I gas did not contribute much to the missing H I in HCGs. Other research explored possible connections between H I deficiencies and hot intragroup X-ray gas but found inconsistent correlations [11]. The improvement in sensitivity of new radio telescopes such as MeerKAT [5] offers new opportunities to track the evolutionary sequence of HCGs and solve the missing H I problem.

This study reports MeerKAT H I observations of six HCGs at intermediate and advanced evolutionary stages. While specific science goals will be addressed in future work, this contribution provides an overview of the observations, descriptions of the data, and our new estimate of the H I deficiency for the observed HCGs. This work is structured as follows: Section 2 introduces the sample, Section 3 details the observations and data processing, Section 4 presents the results, and Section 5 summarizes the findings.

2 Sample

Previous H I observations of our targets are briefly summarized below.

2.1 Phase 2 groups

• **HCG 16:** Using the VLA, [13] detected intricate tidal structures in HCG 16, most notably a 160 kpc tail extending from the core toward NGC 848. [2] obtained the H I spectrum of HCG 16 using the GBT, giving a total mass that is 5% higher than that of the VLA when measured within the same area. The VLA map of [6] revealed an H I tail stretching from HCG 16 to a faint optical counterpart north of HCG 16, which is thought to be a Tidal Dwarf Galaxy (TDG) [9].

• **HCG 31:** H I was previously detected in all core members of the group, ranging from 10% to 80% of the expected values [14]. Note though that the group as a whole is not H I deficient. [14] found numerous tidal features in HCG 31, with all core members showing signatures of interactions. The GBT observations by [2] recovered 70% more H I flux than the VLA.

• **HCG 91:** Previous H I observations of the group showed extended tidal tails, bridges, clumps, a double gaseous component, disturbed velocity field, and asymmetric rotation curves [1]. In addition, all core members of HCG 91, except HCG 91d, have been detected in H I [7]. Using the GBT, [2] detected 38% more flux than those measured with the VLA.

2.2 Phase 3 groups

• **HCG 30:** The VLA failed to detect H I in the core of HCG 30 [7]. However, using the GBT, evidence of the presence of a diffuse H I emission was found by [2] in the form of broad

H I emission spanning the whole velocity range of the group.
• **HCG 90:** NGC 7172 is the only member of HCG 90 that was previously detected in H I [7]. The GBT measured 44% more H I flux than the VLA [2], yet the recovered mass indicates that the group is still highly H I deficient.
• **HCG 97:** The VLA observations of [7] detected H I only on the approaching side of HCG 97b among the five core members of HCG 97. The authors suggested that HCG 97b has a disturbed structure as manifested by the presence of a radio tail and an extended structure to the west of HCG 97b.

3 Observations and data reduction

The observations were carried out between July 31, 2021, and January 02, 2022, using the MeerKAT L-band receiver (856-1711.974 MHz), centered at 1389.1322 MHz, in its 32k correlator mode. The 856 MHz total bandwidth of MeerKAT was divided into 32768 channels of 26.123 KHz (or 5.5 km s^{-1} at 1420.4 MHz). The data was collected using the four linear polarization channels from the MeerKAT antenna feeds (XX, XY, YX, and YY), following the standard South African Radio Astronomy (SARAO) observing strategy. The total time spent on target was about 5.15 hours per group. With calibration overheads, the total time spent per group was ∼6.25 hours (or 37.5 hours in total) using a 8s integration time.
We processed the raw data through the CARACal pipeline [8] to produce science ready data products using a virtual machine of the Spanish prototype of the Square Kilometre Array Regional Centres (SPSRC) [3]. CARACal integrates multiple data-reduction softwares through configurable workflows, allowing the users to customize the sequence of tasks to be executed and tweak parameters based on their scientific goals. To get our final data products, the raw data were processed through three main steps (the so-called "workers"):
• **flagging and cross-calibration:** flag bad data (e.g., due to radio frequency interference (RFI) and cross correlations between antenna) and correct for effects related to the instruments and local observing conditions,
• **continuum imaging and self-calibration:** image the radio continuum emission and calibrate the phase and amplitude of the source using the source model itself,
• **continuum subtraction and spectral line imaging:** subtract the continuum from the spectral windows and image the spectral line emission to create science-ready data cubes. To find H I line emission sources within our data cubes, we use the Source Finding Application (SoFiA) [10] outside of CARACal.

4 Results

• **Data products:** Our main data products consist of data cubes, moment maps of the spectral line, integrated spectra, as well as source catalogues, cubelettes, moment maps, position velocity cuts, and integrated spectra for each source detected by SoFiA. Figure 1 presents a comparison of the integrated spectra from the GBT and MeerKAT, both obtained within the same GBT beam area and smoothed at 20 km s^{-1} velocity resolution. Overall,

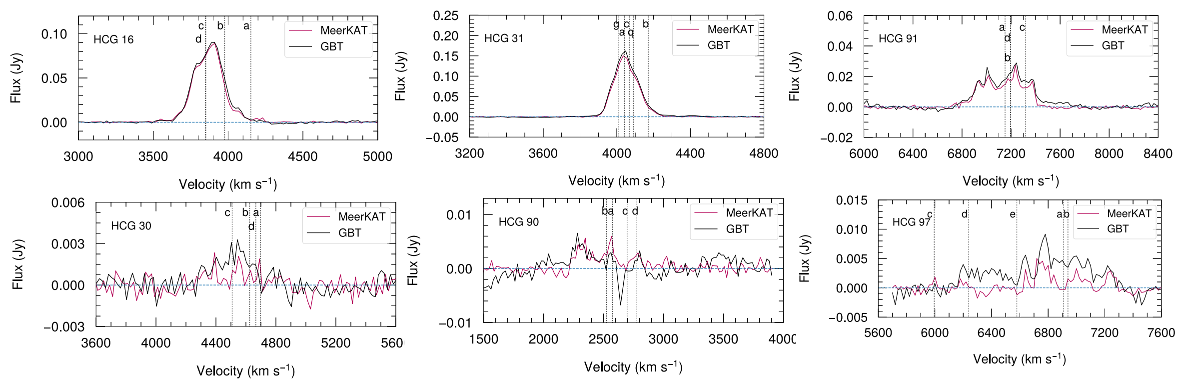

Figure 1: GBT vs MeerKAT integrated spectrum smoothed at 20 Jy km s^{-1}. The pink solid lines indicate the MeerKAT integrated spectra. The solid black lines indicate the GBT spectra of [2]. The vertical dotted lines indicate the velocities of the galaxies in the core of each group. The horizontal blue lines indicate zero intensity values to guide the eyes.

the H I flux recovered by the two telescopes agree well with each other for phase 2 groups. However, the MeerKAT spectra do not show the presence of broad diffuse emission apparent in GBT spectra for phase 3 groups. Figure 2 shows the column density maps of the groups overlaid on the Dark Energy Camera Legacy Survey (DECaLS) DR10 R-band optical images. For phase 2 groups, the MeerKAT maps show more extended H I emission compared to previous VLA maps. In addition, the detected tidal features are much more pronounced than previously found. We also detect many surrounding galaxies, most of which are normal disk galaxies with no apparent signs of interactions. This suggests that the groups might be embedded in larger structures than previously thought. For phase 3 groups, we detect new high surface brightness feautures (e.g., the H I tail at the centre of HCG 90 shown in Figure 2) that were missed by the VLA.

- **H I deficiency :** We estimate the H I deficiency as the difference between the observed H I mass and the predicted H I mass based on the optical luminosity of the group ($\mathrm{def}_{\mathrm{HI}} = \log(M_{\mathrm{HI}}^{\mathrm{pred}}) - \log(M_{\mathrm{HI}}^{\mathrm{obs}})$). In this study, we classify galaxies as H I-normal if their $\mathrm{def}_{\mathrm{HI}}$ values lie within the scatter of the M_{HI} - optical luminosity scaling relation ($-0.42 < def_{\mathrm{HI}} < 0.42$). Galaxies with $\mathrm{def}_{\mathrm{HI}} > 0.42$ are classified as deficient, while those with $\mathrm{def}_{\mathrm{HI}} < -0.42$ are H I-rich. To get an overview of the atomic gas distribution in the core of HCGs and their surrounding galaxies, we examine the H I content of the detected galaxies up to at least one virial radius, r_{vir}. Figure 3 illustrates how the H I deficiency varies with projected distance from the group center. Notably, the figure reveals a clear separation between phase 2 (represented by cool-colored circles) and phase 3 core galaxies (shown as warm-colored circles). Phase 2 galaxies generally display normal H I content, whereas phase 3 galaxies exhibit noticeable H I deficiency especially in the core. Additionally, both phases indicates a gradual decrease in H I deficiency with increasing distance from the group center. This indicates that processes responsible for gas removal in galaxies are much more efficient in the core of the groups than in the surrounding regions.

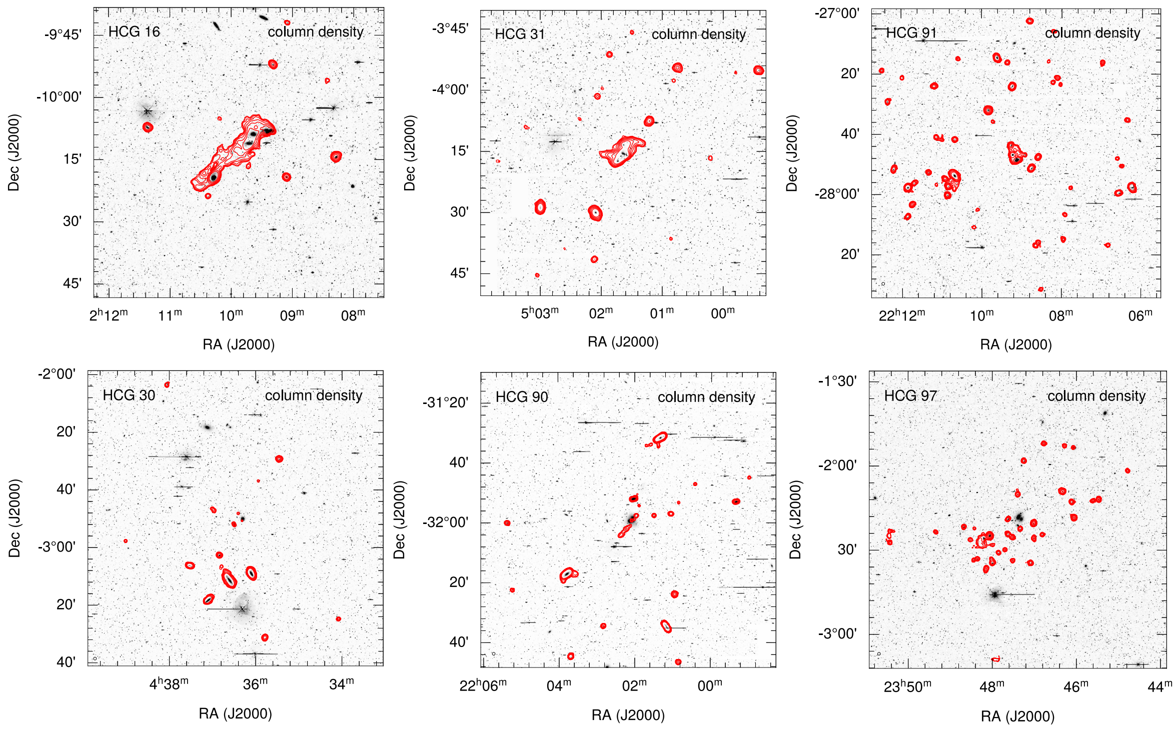

Figure 2: H I column density maps overlaid on DECaLS DR10 R-band optical images. The lowest contour is about 3.1×10^{18} cm^{-2}.

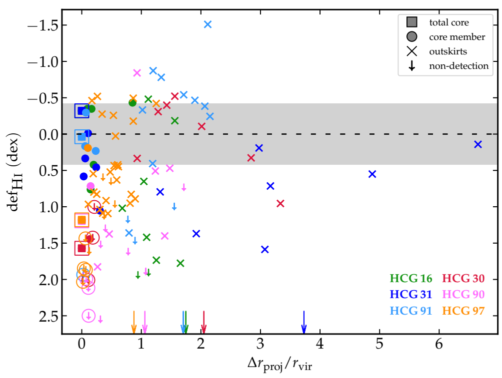

Figure 3: HI deficiency vs. projected distance from group centre in units of r_{vir} for galaxies in and surrounding HCGs. The shaded region, represents the zone of *normal* HI content.

5 Summary

We presented results of MeerKAT H I observations of six HCGs at intermediate and advanced stage of their proposed evolutionary sequence. Our data indicates the presence of numerous tidal feautures in phase 2. Additionally, the extent of the H I emission in this phase is more extended than previously mapped by the VLA. However, we did not detect any diffuse H I emission in phase 3 groups as was apparent in previous GBT spectrum reported in the literature. Our H I maps show numerous galaxies surrounding the groups in both phases, indicating that they are embedded in larger structure than previously thought. Finally, the H I deficiency of the member galaxies tend to decrease as a function of the projected distance from the center of the groups.

Acknowledgments

Authors RI, LVM, and AS acknowledge financial support from the grant PID2021-123930OB-C21 funded by MICIU/AEI/ 10.13039/501100011033 and by ERDF/EU, and the grant CEX2021-001131-S funded by MICIU/AEI/ 10.13039/501100011033, and the grant TED2021-130231B-I00 funded by MICIU/AEI/ 10.13039/501100011033 and by the European Union NextGenerationEU/PRTR, and acknowledge the Spanish Prototype of an SRC (SPSRC) service and support funded by the Ministerio de Ciencia, Innovación y Universidades (MICIU), by the Junta de Andalucía, by the European Regional Development Funds (ERDF) and by the European Union NextGenerationEU/PRTR. The SPSRC acknowledges financial support from the Agencia Estatal de Investigación (AEI) through the "Center of Excellence Severo Ochoa" award to the Instituto de Astrofísica de Andalucía (IAA-CSIC) (SEV-2017-0709) and from the grant CEX2021-001131-S funded by MICIU/AEI/ 10.13039/501100011033

The MeerKAT telescope is operated by the South African Radio Astronomy Observatory, which is a facility of the National Research Foundation, an agency of the Department of Science and Innovation.

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