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Atomic hydrogen discs as tracers of galaxy transformation in Abell 2626 and beyond

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Summary

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The extended, fragile, collisional H i gas discs in galaxies not only provide the raw fuel for star formation, but also serve as diagnostic tracers of gravitational and hydrodynamic environmental processes acting on galaxies. The goal of my PhD is to address the key question “how do cluster galaxies evolve?" The aim of my PhD is to obtain an H i perspective on the origin of the morphology-density relation. For this I have used state-of-the-art research instruments: both by studying the atomic hydrogen gas content in relation to the star formation (SF) rate in a population of galaxies in a cluster environment and by a detailed analysis of the multi-phase gaseous components in a few striking galaxies. On a broader scale, I am investigating how the local and global cosmic environment of galaxies in clusters influence their H i morphologies and star formation activities. I have studied the H i deficiencies and spatially resolved morphologies of the H i detected galaxies in and around the Abell 2626 galaxy cluster from MeerKAT observations. On a smaller scale, I have studied so-called ‘jellyfish galaxies’ (JFGs), which are extreme examples of ram-pressure stripping (RPS) with *in situ* star formation in their tail.

6.1 Thesis highlights

6.1.1 The H i content of galaxies in and around Abell 2626

To gain an H i perspective on the gas removal and depletion mechanisms acting on galaxies that are being accreted by a moderately massive galaxy cluster, we conducted a volume-limited H i imaging survey with the MeerKAT radio telescope, centred on the galaxy cluster Abell 2626. In the entire survey volume, 219 galaxies with an optical counterpart are detected in H i of which 46 galaxies are in the cluster proper, 30 galaxies are located in cluster substructures and 21 galaxies are detected in the Swarm. In Chapter 2, I have presented the H i properties of the H i detected galaxies with tables and an atlas page for each galaxy, including an H i column-density map, a velocity field, a position-velocity diagram, and a global H i profile. Finding H i sources in the H i cube was a major challenge. In particular, to balance the trade off between completeness and reliability of the H i detected source population, I have adopted an empirical approach by applying SoFiA multiple times with different parameter settings and selecting the SoFiA mask with the highest signal-to-noise.The goal was to identify the diverse population of galaxies in our survey volume, ranging from nearby dwarfs to distant early-type galaxies, given the good sensitivity yet spatially variable, the redshift depth, and the relatively coarse spectral resolution of the MeerKAT data.

6.1.2 Characterising H i morphologies of galaxies

H i asymmetries in galaxies are considered to be indicative of the effects of the environment in which the galaxies are residing. My aim was to study the asymmetries of the H i discs in

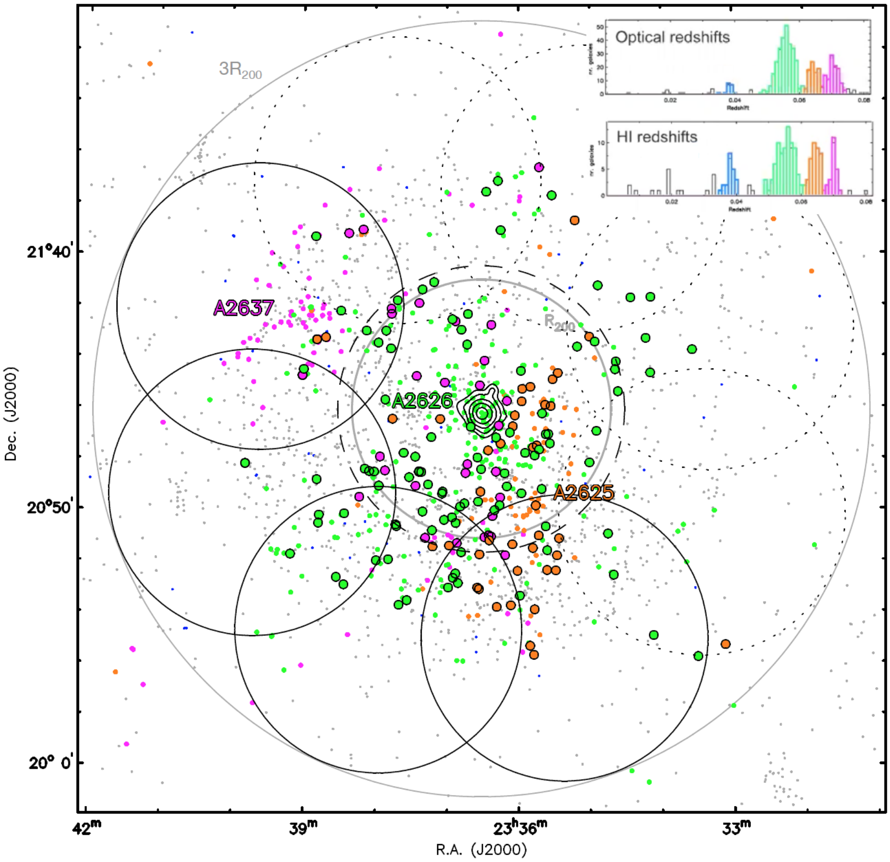

Fig. 6.1: Distribution of the galaxies detected in A2626, its surroundings and two background over-densities. Encircled coloured symbols are H I detected galaxies, different colours indicate different over-density regions that are shown in the inset. Small points show other galaxies within the MeerKAT bandpass ($z < 0.45$). Large solid circles indicate the FWHM of the 4 proposed MeerKAT pointings, reaching out to $3R_{200}$. The dashed circle indicates the existing MeerKAT pointing (4k mode). Central contours show ROSAT X-ray emission from A2626. Dotted circles indicate potential future MeerKAT pointings. Insets show histograms of optical and H I redshifts, tracing the same over-densities.

galaxies in and around A2626 in relation to their local environment and then investigate which characterisation is sufficiently robust to assess the H I morphologies of the galaxies in our sample. I first identified the galaxies with sufficient signal-to-noise and angular resolution and considered them for further analysis. To quantify asymmetries of the outer H I disc of individual galaxies, I used 1) three different visual classes based on the outermost reliable H I contour (settled, disturbed, unsettled H I discs), 2) offset of the H I centre with respect to the optical centre of a galaxy, and 3) the modified asymmetry parameter A_{mod} as defined by Lelli et al. (2014). The latter depends on how well a galaxy is spatially resolved, the choice of the galaxy centre, and the H I column density above which A_{mod} is measured. To calculate A_{mod}, I used an H I column density level of 25×10^{19} cm^{-2}, at least 3 synthesized beam (15") to fit within that contour, and a minimum peak signal-to-noise of 5 in the H I map.

6.1.3 Environmental effects on the H I morphologies of galaxies

In and around A2626, there are three main environments with a significant number of H I detections: non-substructure or 'isolated' galaxies in A2626 (cluster environment), substructure galaxies in A2626 (groups influenced by the cluster environment) and the Swarm galaxies (group environment). I investigated if environment has any influence on the H I deficiency, H I morphology, and the star formation deficiency of the H I detected galaxies. There is a strong correlation between H I deficiency and projected distance from the centre of A2626. Moreover, substructure galaxies tend to be more asymmetric than the isolated galaxies in A2626 plausibly due to more efficient tidal interactions in substructures than outside substructures. Next, after exploring whether the shapes of the outer H I discs are affected by various physical mechanisms driving H I deficiencies in different environments in and around A2626, I found that asymmetric, offset, and smaller H I discs are not necessarily the result of the cluster environment, as they are also observed in substructures in A2626 and in the Swarm. This implies that pre-processing of the H I discs plays an important role. Finally, the galaxies in all three environments seem to have slightly lower SFRs than the typical SFR for normal galaxies, hinting at effective gas removal mechanisms in the cluster environment ('processing') as well as in the substructures and the Swarm ('pre-processing').

6.1.4 The H I content of extreme ram-pressure stripped jellyfish galaxies

I have explored the multi-phase ISM of two jellyfish galaxies JW100 (in the A2626 cluster) and JO204 (in the A957 cluster) to investigate the physical mechanisms shaping the striking jellyfish tails. Following are some interesting findings from my analysis.

Jellyfish vs. non-jellyfish galaxies

Compared with the reference sample of galaxies residing in cluster and field environments, jellyfish galaxies seem to have lower H I masses for their stellar masses. When the SFR in the jellyfish galaxies is compared to the SFR in the reference sample galaxies, the jellyfish galaxies stand out in the relation. This signifies that although jellyfish galaxies are significantly stripped due to ram-pressure, the little H I left in them is efficiently forming stars. Thus, 'jellyfish' is an unique 'state' of a massive galaxy at a dense cluster core, which in spite of having lost most of its gas reservoir, continues to form stars efficiently.

The multiphase ISM of jellyfish galaxies

The H I tail (90 kpc, from VLA-C observations) of jellyfish galaxy JO204 is extended far beyond the ionised gas tail (30 kpc, from MUSE observations). The north-western part of the H I gas disc still retains some neutral and ionized gas in JO204 while the south-eastern part is already

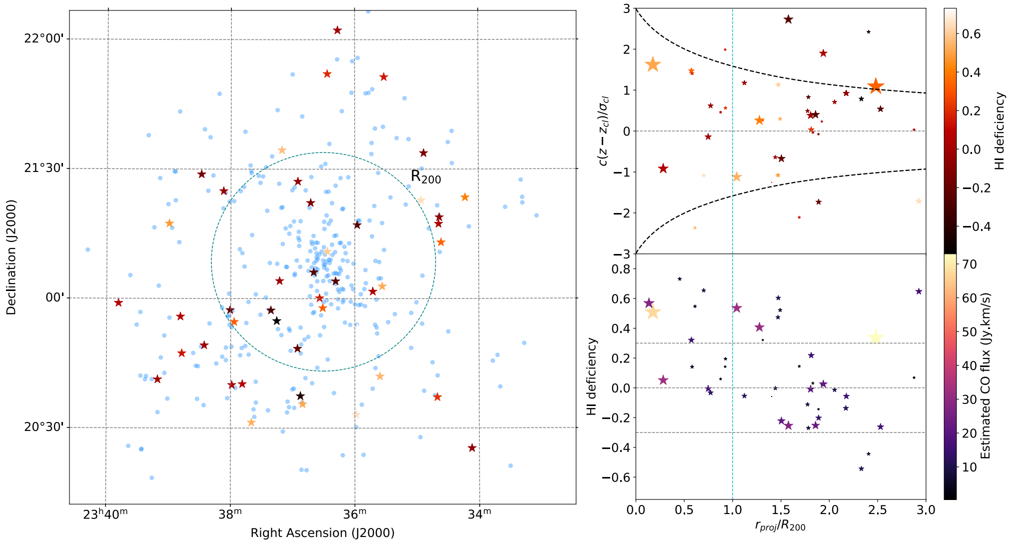

Fig. 6.2: **Left**: Distribution of galaxies in A2626 in the sky. The dotted circle indicates the R_{200} of A2626. The star markers represent the ALMA target galaxies with their colours representing their H I deficiencies (see colourbar of the top-right panel). The blue points are other cluster galaxies with optical redshifts. **Upper right**: The distribution of galaxies in projected phase-space of A2626. The black dashed lines indicate the cluster escape velocity. The star markers represent the ALMA target galaxies with colours representing their H I deficiencies and sizes indicating their estimated CO fluxes. **Bottom right**: H I deficiencies of the galaxies in A2626 as a function of projected distance from the cluster centre, normalised by R_{200}. H I deficiencies follow from scaling relations (Dénes et al., 2014) based on optical diameters (negative deficiency: H I rich, positive deficiency: H I poor). The star markers represent the ALMA target galaxies, with both sizes and colours representing their estimated CO fluxes based on their 1.4 GHz radio continuum emission. The vertical dotted line indicates the R_{200} of A2626.

depleted due to ram-pressure, creating an extension in the H I tail to the east and causing an asymmetry in the H I emission profile. Moreover, the atomic and ionised gas phases are not always cospatial in different velocity channels. This indicates that the ram-pressure stripped tail consists of a highly turbulent medium, where the scattered young stars ionise the H I gas locally to produce Hα emission.

H I observations of jellyfish galaxy JW100 reveal an extended H I tail to the south-west, $\sim$ 50 kpc from the stellar disc of the galaxy. Comparing the Hα (from MUSE observations), CO(2-1) (from ALMA observations), and H I (from MeerKAT observations) emission in various velocity channel maps in JW100, I found Hα emission in the northern part of the RPS tail with no CO(2-1) or H I emission (but where X-ray emission is present, see Poggianti et al. 2019) probably as a result of a complex ISM-ICM interaction due to a prolonged influence of ram-pressure stripping. Moreover, there is an anti-correlation observed between the distribution of Hα and CO(2-1) versus H I, hinting at an efficient conversion of H I to H_2 in the tail. The hypothesis is that the draping of the magnetic field around the tail is possibly preventing thermal conduction and hydrodynamic turbulence by the hot ICM, enabling the stripped H I gas to cool and condense into H_2 clumps (e.g. Müller et al. 2021).

Various H I depletion channels of jellyfish galaxies I estimated the relative importance of the three main depletion mechanisms of the H I gas in jellyfish galaxy JW100. The three main depletion channels are: 1) ram-pressure stripping of the H I gas, 2) conversion of the H I gas into H_2, and 3) ionisation of the H I gas into Hα. I estimated that ram-pressure has removed at least 70% of the H I gas from the disc of JW100. The clumpy H_2 gas in the tail is converted *in situ* from H I gas and constitutes $\sim$25% of the total amount of hydrogen in the tail. Hence, JW100 has already lost almost 80% of the expected H I mass based on the $M_{HI}/M_{\star}$ scaling relation for field galaxies (Maddox et al., 2015). I conclude that JW100 is at a very advanced stage of gas removal and the depletion mechanisms have removed most of the H I gas from it already.

Is AGN activity induced by ram-pressure stripping in jellyfish galaxies?

Poggianti et al. (2017a) have found a very strong correlation between ram-pressure stripping and AGN activity. To investigate if ram-pressure induces AGN activity in jellyfish galaxies, I have modelled the H I absorption profile in the jellyfish galaxy JO204 using the ionized gas as representative of the H I gas kinematics. The model H I absorption profile is wider than the observed profile. Hence, the observed redshifted wing can be accommodated within the velocity range of the model absorption profile. Consequently, the observed asymmetric H I absorption profile can be explained by a clumpy, rotating H I gas disc seen partially in front of the central continuum source, or by ram pressure pushing the neutral gas towards the centre of the continuum source, triggering the AGN activity. I conclude that the relation between ram-pressure stripping and AGN activity could not be identified unambiguously in JO204 and that high angular resolution observations are necessary to further test the hypothesis.

6.2 Future work: The PRABHA Survey

My plan is to broaden the work on understanding the environmental processes acting on the multi-phase (atomic, molecular, ionised) ISM of galaxies in various environments (groups, clusters and filaments) and at different stages of evolution, taking advantage of the state-of-the-art telescopes like MeerKAT, ALMA, SMA, INT, and WEAVE. In particular, the PRABHA (PRe-processed And Backsplash galaxies from a multi-phase Hydrogen Approach, ‘PRABHA’ meaning ‘light’ in the Sanskrit language as well as the name of an Indian mythological goddess of strength and power) survey will shed light on the multi-phase gas accretion and removal processes in galaxies residing in the outskirts of A2626, that might be infalling and ‘pre-processed’ galaxies, or ‘backsplash’ galaxies that have already crossed the peri-centre once.

I. HI observations: We have recently been awarded 48 hours of MeerKAT observations in 32k mode (PI: T.Deb) to extend the area around A2626 that is covered by our existing, single MeerKAT pointing, to a radial range of 1-3 R_{200} (see Fig. 6.1). My principal science objective is to explore the importance of ‘pre-processing’ of galaxies in the cosmic large scale structure in which A2626 is embedded before they reach the inner cluster environment. I will also investigate the gas content of so-called ‘back-splash’ galaxies that were once inside R_{200} on their infall trajectory. The observational goal is to image the morphologies and kinematics of the H I discs of galaxies located at the outskirts of the cluster, as they are sensitive diagnostic tracers of various gravitational and hydro-dynamical processes at play.

The scientific analysis of our MeerKAT data will be further enhanced by forthcoming ancillary data. Synergy with LOFAR will allow spectral index mapping. Analysis of the hydrodynamical simulations will provide insights in the gas removal processes.

II. Stellar populations: I am collaborating with the WEAVE Wide-Field Cluster Survey team to obtain redshifts, metallicities, velocity dispersions and recent star formation histories for galaxies in A2626 out to $5R_{200}$.

III. CO observations: We have recently been awarded 24 hrs of ALMA time (PI: T. Deb) and 3 tracks at the SMA observations (PI: T.Deb) to target ~ 50 star forming galaxies with a range of H I deficiencies in A2626, from H I deficient to H I rich galaxies with signatures of ram-pressure, harassment, tidal interaction etc to measure the molecular gas content in them (see Fig. 6.2). Moretti et al. (2020a) recently found extended ram-pressure stripped molecular gas tails in H I deficient jellyfish galaxies, unlike previous findings in Virgo galaxies (Lee et al., 2017). Thus, it is imperative to investigate the molecular gas content compared to the atomic gas content to understand the driving mechanisms of star formation in galaxies residing in all cosmic environments, ranging from voids to the dense cores of galaxy clusters. In particular, with its exceptional resolution and sensitivity, ALMA observations of galaxies in A2626 within a range of cosmic environments will shed light on how environmental processes such as ram pressure stripping and tidal interactions affect the more tightly bound and centrally located molecular gas in these galaxies.

IV. Hα and UV observations: Our team has been awarded 3 dark nights of INT (PI: M. Verheijen & R. Smith) to investigate the ionised ISM and study the interplay of atomic, molecular, and ionised ISM. We have conducted deep imaging of the Hα emission across Abell 2626, from the cluster core to its infall regions. The scientific goal is to characterise the star formation activity and the presence of extraplanar ionised gas associated with galaxies located in the various environments in and around A2626.

V. Simulations: I intent to relate our findings regarding the amount and distribution of the multi-phase Hydrogen gas in galaxies across various cosmic environments, to the results from hydrodynamical cosmological simulations. This will further constrain the physical models of the simulations and at the same time provide further insights in the astrophysical processes that act on the gaseous constituents of evolving galaxies in transformation.