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INVESTIGATING NEUTRAL HYDROGEN CONTENT IN RADIO MOHEGS AND PROSPECTS WITH THE SKA

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Abstract. Most of the interstellar matter in galaxies occurs in the form of cold neutral hydrogen (H I) gas, which is the primary fuel for star formation. Observations of the H I 21-cm line absorption help understand the kinematics of gases, the overall star formation activities within the galaxies, and their interaction with the neighbouring environment. This paper presents the first systematic H I study of radio MOlecular Hydrogen Emission Galaxies (MOHEGs). These massive galaxies show FRI/II type radio morphology, high-luminosity molecular hydrogen emission, and weak Polycyclic Aromatic Hydrocarbon (PAH) emission indicative of a low star formation rate. Neutral hydrogen (H I) column density down to 10^{20} cm^{-2} is detected in 50% (7/14) galaxies within our sample at a distance of a few kiloparsec scales from the nearest neighbours. Our results suggest that radio MOHEGs are deficient in H I, and various factors, such as nuclear radio activities in central regions, the density of their environment (low or high), the evolutionary stage of these galaxies, play a role in regulating the presence of neutral gas. Next-generation radio telescopes such as the Square Kilometre Array (SKA) and pathfinder instruments will not only trace the evolution of H I 21-cm absorbers systems from nearby up to intermediate redshift Universe at unprecedented depths but also revolutionize our understanding of galaxy evolution across different environments, gas inflows-outflows, interaction with the intragalactic medium, and probe the era of galaxy evolution at the cosmic noon (1 < z < 3).

Keywords: Galaxies: absorption lines - Galaxies: evolution - Galaxies: Interstellar medium

1 Introduction

Recent studies from the IR Spitzer telescope have revealed an exciting class of 17 (FR-I and FR-II) radio MOlecular Hydrogen Emission Galaxies (radio MOHEGs) at redshift $z < 0.22$. These galaxies have ample amounts of molecular hydrogen gas masses ($\sim 10^{10}$ M$\odot$), though they are inefficient at star formation, suggesting that the molecular gas is kinematically unsettled and turbulent. The star formation in these galaxies is critically affected due to molecular gas heating, preventing the gas from cooling down to form stars. These galaxies show a significantly larger L(H_2) /L(PAH) ratio (0.03-4 or greater) as compared to normal star-forming galaxies. The pure rotational and ro-vibrational H_2 transitions give rise to H_2 luminosities of the order of 10^{40}-10^{42} ergs^{-1}, along with a relatively weak IR continuum emission L(H_2)/L(IR) $>10^{-3}$, that acts as the primary coolant for the warm molecular phase of the ISM, with a very short cooling timescale ($\sim 10^4$ years) (Ogle et al. 2010). In addition, these galaxies belong to galaxy clusters or close interacting pairs or groups. The high observed molecular mass may be linked to gas-rich galaxy collisions/interactions or cooling flows, which drive gas into the central less gas-rich environments in radio galaxies (Ogle et al. 2007).

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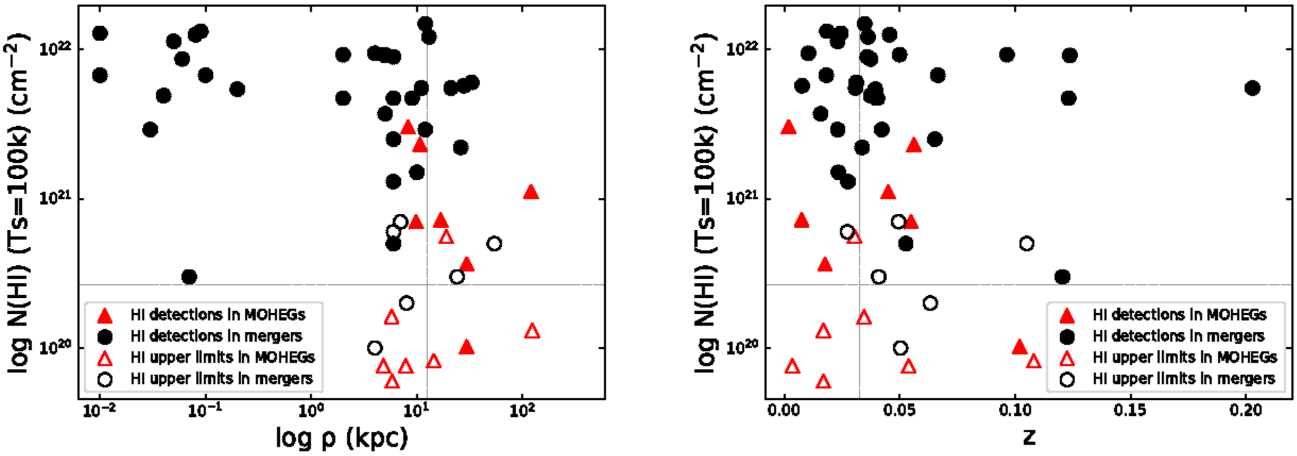

Fig. 1. Neutral hydrogen column densities of the radio MOHEG sample sources along with a sample of mergers following the same distribution as a function of interaction distance between the nearest neighbour (left panel) and redshifts (right panel). The dotted lines represent median values derived from the MOHEG sample. The median N(H I) value is 2.64 x 10^{20} cm^{-2}, the median redshift is 0.03241, and the median separation is 12.58272 kpc.

Moreover, it is not only the H_2 gas abundance but also the atomic gas in galaxies that plays a significant role in star formation and galaxy evolution. It acts as an important intermediary component in the baryon cycle, a reservoir of the raw fuel for star formation, and leads to the formation of H_2 gas via exothermic processes. It is inferred from previous studies that extended atomic gas in the disc regions of the gas-rich systems is highly exposed to distortions caused by tidal interactions, ram pressure stripping, and merging activities in dense environments (Yun et al. 1994; Brown et al. 2017). In addition, the atomic gas is also heated up by chemical, radiative, and mechanical feedback linked with star formation activities (Cox & Smith 1974; Wolfire et al. 1995). The imprints of such interactions can be studied through H I 21cm absorption line studies. It can complement the emission line surveys to trace the evolution of the atomic gas component in and around galaxies. The H I absorption features depend on the strength of the background radio continuum and are independent of the distance of the source. The H I 21-cm optical depth-integrated over velocity is proportional to the column density of neutral hydrogen, N(H I) cm $^{-2}$ is given by,

$$N_{\rm HI} = 1.82 \times 10^{18} \frac{\rm T_s}{f_c} \int \tau d\nu \ \ ({\rm cm}^{-2}) \tag{1.1}$$

where T_s (K) is the spin temperature of the gas, f_c is the fraction of the background radio source covered by the absorbing gas (Rohlfs & Wilson 2000).

In this paper, we discuss the importance of studying cold neutral gas content in radio galaxies rich in molecular hydrogen to probe the role of atomic hydrogen gas in explaining the influence of surrounding environments on galaxy evolution over cosmic timescales. In § 2, we present the results of our study of neutral hydrogen gas distribution in the radio MOHEGs and their dependence on the galaxy properties. The prospects of SKA in studying the H I properties of MOHEGs type galaxies are discussed in § 3, and the conclusion of this work is discussed in § 4.

2 N(H I) and kinematics

The H I column density in galaxies serves as a crucial indicator of their gas content, offering valuable insights into various aspects such as morphology, gas composition, dynamical activities, and interactions with their neighbouring environments. Additionally, it allows us to investigate the locations of active star formation and provides information on the kinematics of gas within these galaxies. In our study, we calculated the average N (H I) for our MOHEG sample. The results presented are based on the H I data taken from the literature. The H I column density within our sample ranges from ≈ 6 $\times 10^{19}$ cm^{-2} to 3.03 $\times 10^{21}$ cm^{-2}, assuming a spin

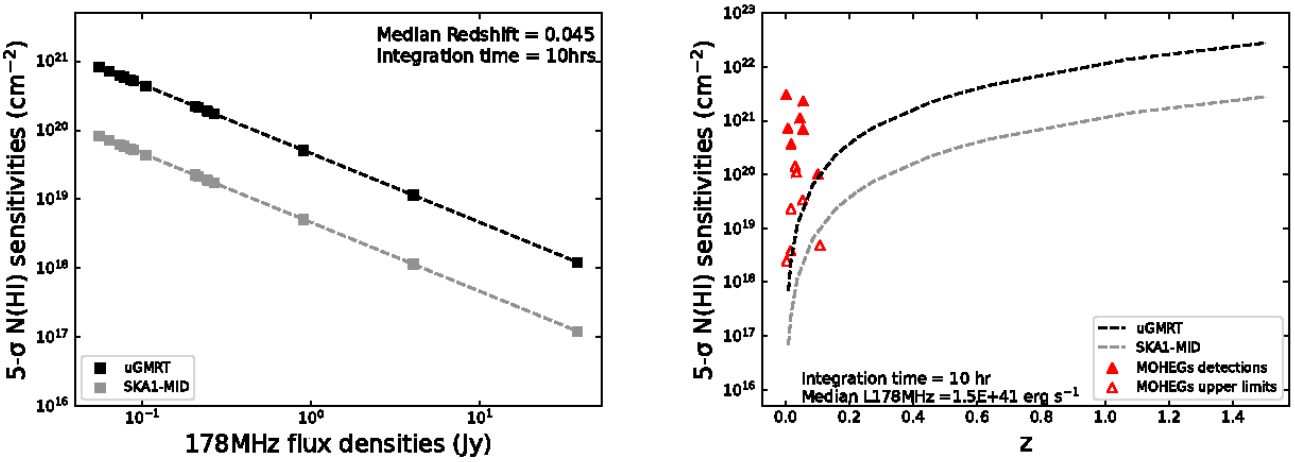

Fig. 2. 5σ N(H I) absorption sensitivities for MOHEGs-type sources for SKA1-MID (grey line) and uGMRT (black line) for 10hrs integration times with respect to the 178MHz flux densities (left panel) and redshifts (right panel). The radio MOHEGs sample is plotted in red triangles.

temperature of 100K. Existing data in the literature suggests that the average column density for the H I disk in spiral galaxies typically falls around 10^{20} cm^{-2} (Wang et al. 2016; Serra et al. 2012). Consequently, MOHEGs exhibit a wide range of column densities; however, only 50% of galaxies in our sample show neutral hydrogen detection, with H I column densities reaching as low as 10^{20} cm^{-2}. We suggest that the radio MOHEGs are class of galaxies engaged in merging stages, with N(H I) values a factor of 18 lower compared to the merger sample, where the median N(H I) $\sim 5 \times 10^{21}$ cm^{-2} (Dutta 2019), refer Figure 1. Furthermore, there is no specific trend in the H I column density distribution concerning the nearest neighbour distance and redshift for both samples. This result suggests that radio MOHEGs are deficient in atomic hydrogen compared to merging galaxies at similar redshifts and distances due to their dense neighbouring environment, leading to enhanced gas stripping. Understanding the link between H I absorption properties and the feedback mechanisms that trigger or quench star formation in galaxies is essential for investigating the turbulence generated in the cold hydrogen gas and the interplay between atomic and molecular gas in explaining the properties of these galaxies during mergers within the intergalactic medium (Wagh et al. 2023).

3 SKA HI survey and prospects

In Figure 2, we plot the sensitivity for H I detections in MOHEG-type sources at different flux densities, observation times, and redshifts for the SKA1-MID and uGMRT. We used the extrapolated values at 178 MHz flux densities and the median redshift of the total MOHEGs sample to compute the flux densities of the background continuum sources (Ogle et al. 2010), using a power-law scaling of -0.7 spectral index (a typical value for radio galaxies). The theoretical RMS noise was calculated for a given integration time at a 5 km s^{-1} channel width for all the instruments (Blyth et al. 2015; Bharti & Bagla 2022; Maddox et al. 2021; Braun et al. 2019). The 5σ sensitivity limits on H I detections for different instruments at different integration times are plotted in Figure 2. For a reasonable integration time up to $\sim$ 10 hrs on a strong background continuum source, we will detect sources with N(H I) column densities as low as $\sim 10^{17}$ cm^{-2} for the SKA1-MID bands, whereas we will be limited to $\sim 10^{18}$ cm^{-2} with the uGMRT. Further, due to the narrow band observations and poor sensitivities (mJy-level) offered by the SKA precursor instruments, H I detections in MOHEGs-type galaxy samples have been limited to the z $\sim$ 0.2 range, however; upcoming telescopes like SKA1-MID can detect much deeper and fainter absorption features (a factor of 2 and above better) with the same integration times as shown in Figure 2 panel 2. These plots suggest that in shallow surveys, SKA1-MID will efficiently detect N(H I) column densities up to a redshift of z $\sim$ 1.5 for a bright population of background sources, thereby probing the cosmic noon regime where star formation activities show a peak. SKA will thus discover a new class of low-column-density absorbers around galaxies with extended or compact morphologies based on their surrounding environments.

4 Conclusions

In this study, we systematically investigated the neutral hydrogen gas in radio MOHEGs using the H i 21-cm absorption line and assessed the prospects for conducting such studies with the SKA and pathfinder telescopes. The key results of our work are summarized below:

- Radio MOHEGs exhibit a deficiency in atomic hydrogen, with a median value of 2.64 x 10^{20} cm^{-2}, compared to merging galaxies at similar redshifts. This deficiency can be attributed to their dense neighbouring environments, which lead to reduced H i gas quantities due to tidal forces, stripping, and strangulations.

- There exists no clear correlation between H i gas column densities and the galaxy properties below z $\sim$ 0.2.

- The SKA is poised to efficiently detect low column density features, enabling the tracing of the complete gas cycle from disks to the intergalactic medium (IGM), including tails and filaments that indicate the phases (pre-, post-, ongoing) of merger events and AGN-induced feedback mechanisms. Importantly, it will provide comprehensive data to trace the entire evolution of H i from the current epoch up to the cosmic noon within a reasonable observation time, allowing us to probe the star formation history of the universe.

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