A Green Pea starburst arising from a galaxy-galaxy merger

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ABSTRACT

Green Pea galaxies are low-redshift starburst dwarf galaxies, with properties similar to those of the high-redshift galaxies that reionized the Universe. We report the first mapping of the spatial distribution of atomic hydrogen (HI) in and around a Green Pea, GP J0213+0056 at $z = 0.0399$, using the Giant Metrewave Radio Telescope (GMRT). Like many Green Peas, GP J0213+0056 shows strong HI 21 cm emission in single-dish spectroscopy, strong Lyα emission, and a high [OIII]λ5007A/[OII]λ3727A luminosity ratio, O32 $\approx 8.8$, consistent with a high leakage of Lyman-continuum radiation. Our GMRT HI 21 cm images show that the HI 21 cm emission in the field of GP J0213+0056 arises from an extended broken-ring structure around the Green Pea, with the strongest emission coming from a region between GP J0213+0056 and a companion galaxy lying $\approx 4.7$ kpc away, and little HI 21 cm emission coming from the Green Pea itself. We find that the merger between GP J0213+0056 and its companion is likely to have triggered the starburst, and led to a disturbed HI spatial and velocity distribution, which in turn allowed Lyα (and, possibly, Lyman-continuum) emission to escape the Green Pea. Our results suggest that such mergers, and the resulting holes in the HI distribution, are a natural way to explain the tension between the requirements of cold gas to fuel the starburst and the observed leakage of Lyα and Lyman-continuum emission in Green Pea galaxies and their high-redshift counterparts.

Keywords: Galaxies — starburst, Galaxies — dwarf, Galaxies — 21 cm line emission

1. INTRODUCTION

Faint star-forming dwarf galaxies have long been believed to be the main contributors of the Lyman-continuum (LyC) photons that ionized the Universe during the Epoch of Reionization (EoR) at $z \gtrsim 6$ (e.g. Fan et al. 2006). However, how the LyC photons escaped the EoR galaxies remains an open question today. Direct studies of these high-redshift galaxies is challenging due to limitations in both sensitivity and resolution. Studies of local analogs of the EoR galaxies, i.e. nearby galaxies with high escape fractions of LyC and Lyα photons, hence provide an interesting avenue to understand the processes that led to cosmic reionization.

Green Pea galaxies are extreme emission-line galaxies with compact sizes, low metallicities, and high specific star formation rates, lying at low redshifts, $z \lesssim 0.3$ (Cardamone et al. 2009). They are the most extreme of the actively star-forming galaxies in the local Universe, with Hβ luminosities of $\approx 10^{41} - 10^{42}$ erg s$^{-1}$; for comparison, the “classic” luminous blue compact dwarf galaxy, I Zw 18, has an Hβ luminosity of $\approx 5 \times 10^{39}$ erg s$^{-1}$, two orders of magnitude lower than that of typical Green Peas. Similarly, while galaxies of the Lyman Alpha Reference Sample (LARS; Östlin et al. 2014) have Hβ luminosities similar to those of Green Peas (e.g. Pardy et al. 2014), eight of the 14 LARS galaxies do not meet the Lyα rest equivalent width criterion, $\geq 20$Å, used to identify high-$z$ Lyα emitters (and, in fact, only one LARS galaxy, LARS14, would classify as a Green Pea). Conversely, Green Peas typically show strong Lyα emission (Henry et al. 2015; Yang et al. 2016, 2017), with an equivalent width distribution matching that of high-redshift ($z \gtrsim 3$) Lyα-emitting galaxies (Yang et al. 2016). Izotov et al. (2016, 2018b,a) found LyC leakage in more than ten Green Peas, with escape fractions $2 - 72\%$, making them the strongest known LyC leakers in the local Universe. These lines of evidence suggest that Green Peas are excellent low-$z$ analogs of the galaxies that drove cosmological reionization.

A conundrum in our understanding of Green Peas is the need for sufficient cold neutral gas to fuel the starburst and yet a low enough HI column density to al-
low the Ly$\alpha$ and LyC photons to escape. Recently, Kanekar et al. (2021) used the Arecibo Telescope and the Green Bank Telescope (GBT) to detect H$\text{\textsc{i}}$ 21 cm emission from 19 Green Peas at $z \approx 0.02 - 0.1$. Two of the Green Peas with H$\text{\textsc{i}}$ 21 cm detections, GP J0213+0056 at $z = 0.0399$ and GP J1200+2719 at $z = 0.0812$, are remarkable as they show both strong H$\text{\textsc{i}}$ 21 cm emission and strong Ly$\alpha$ emission, with Ly$\alpha$ escape fractions of $\approx 0.12$ and $\approx 0.39$, respectively (McKinney et al. 2019). Both galaxies also have a high ratio of the $[\text{OII]}\lambda 5007$ luminosity to the $[\text{OII]}\lambda 3727$ luminosity, O32 $\approx 8.8$ (GP J0213+0056) and O32 $\approx 12.9$ (GP J1200+2719), suggesting a high escape fraction of LyC radiation (Jaskot & Oey 2013; Izotov et al. 2016, 2018b), although we emphasize that neither galaxy has so far been detected in LyC emission. However, both galaxies are also “gas-rich” (Kanekar et al. 2021), lying $>2\sigma$ above the local relation between the H$\text{\textsc{i}}$ mass and the absolute B-magnitude (Dénes et al. 2014). These are currently the two best candidates to directly assess the conditions that allow the detection of both H$\text{\textsc{i}}$ 21 cm and Ly$\alpha$ emission from a single galaxy. In this Letter, we report a Giant Metrewave Radio Telescope (GMRT) H$\text{\textsc{i}}$ 21 cm mapping study of GP J0213+0056 at $z = 0.0399$, which has yielded the first determination of the spatial distribution of H$\text{\textsc{i}}$ in and around a Green Pea galaxy.

2. OBSERVATIONS AND DATA ANALYSIS

We observed GP J0213+0056 (J2000 co-ordinates: 02h13m06.6s, +00d56′12.5″) with the GMRT Band-5 receivers on 20-21 December 2019 (proposal 37_056; PI Chengalur). The observations used a bandwidth of 4.17 MHz, centred at 1373.67 MHz and sub-divided into 512 channels, with two polarizations. The GMRT Software Backend (GSB) was used as the correlator. The total on-source time was $\approx 8.4$ hours. Observations of 3C48 were used to calibrate the flux density scale and the system bandpass, while J0204+152 was used as the phase calibrator.

The data were analysed using standard procedures in the Common Astronomy Software Applications (casa Version 5.6; McMullin et al. 2007) package. We initially removed all visibilities from non-working antennas or affected by radio frequency interference (RFI) from the data set. We then used the calibrator data to determine the antenna-based gains and bandpass shapes, using the routines gaincalR and bandpassR (Chowdhury et al. 2020), and applied the gains and bandpass solutions to the target data. We then made a continuum image of the GP J0213+0056 field from the line-free channels, using the routine tclean and the w-projection algorithm. A standard iterative self-calibration procedure was then used, with a number of rounds of phase-only self-calibration and imaging, followed by inspection of the residual visibilities and further data editing to remove any data affected by RFI. The procedure was carried out until no improvement was seen in either the image or the residual visibilities on further self-calibration.

The signal-to-noise ratio of the data was not sufficient

| Beam UV range (′′ × ′′) | RMS noise (mJy Bm$^{-1}$) | $N_{\text{HI}}$ ($\times 10^{20}$ cm$^{-2}$) |
|------------------------|--------------------------|------------------|
| 37 × 32                | 5                        | 0.98              |
| 16 × 16                | 12                       | 0.91              |
| 12 × 12                | 13.5                     | 0.87              |
| 9 × 9                  | 20                       | 0.74              |
| 7 × 7                  | 25                       | 0.66              |

Table 1. Details of spectral cubes made at different resolutions. The columns are (1) the FWHM of the synthesized beam used to make the spectral cube, (2) the UV cutoff used for each cube, in k-wavelengths, (3) the RMS noise at a velocity resolution of 10 km s$^{-1}$, and (4) the 3$\sigma$ H$\text{\textsc{i}}$ column density sensitivity, at a resolution of 10 km s$^{-1}$.
to solve for both the amplitudes and the phases of the complex gains; we hence retained the gain amplitudes from the original calibration. The final continuum image has an angular resolution (full width at half maximum, FWHM, of the synthesized beam) of $2.4'' \times 1.8''$ and a root-mean-square (RMS) noise of $\approx 76 \mu$Jy Beam$^{-1}$. The positions of point sources in the GMRT image are in excellent agreement with their positions in the 1.4 GHz image of the FIRST survey (Becker et al. 1995), within $\approx 1.8''$ (i.e. less than half the FWHM of the FIRST synthesized beam). After applying the final gain solutions to the target data, we subtracted the cleaned continuum emission from the self-calibrated visibilities to obtain a residual visibility data set.

The unique GMRT antenna configuration, with a mix of short, intermediate, and long baselines, allowed us to make spectral cubes at a range of angular resolutions, providing information on both the total H$_i$ content of GP J0213+0056 and the spatial distribution of the H$_i$. For each resolution, we first made a continuum image at the same resolution, and subtracted it out. We then made the spectral cube at this resolution from the residual visibilities. The cubes were made at resolutions of 35'', 16'', 12'', 9'', and 7'', in the barycentric frame, with a velocity resolution of 10 km s$^{-1}$.

The cubes were made with the tclean routine, cleaning the regions that showed H$_i$ 21 cm emission down to a threshold of 0.5 times the per-channel RMS noise. We used robust weighting (Briggs 1995), with robust = 1 at 35''-resolution and robust = 0 for the higher-resolution cubes. This was done in order to increase the sensitivity at the lowest (35'') resolution in order to pick up the entire H$_i$ 21 cm emission, and to reduce sidelobes in the higher-resolution cubes where we aim to accurately map the H$_i$ 21 cm emission. Finally, we used the task immoments in casa and momnt in the Astronomical Image Processing System (AIPS; Greisen 2003) to obtain velocity moments of the spectral cubes, to study the H$_i$ spatial and kinematic distributions. All moment images were made from the ten velocity channels that were found by visual inspection to contain the H$_i$ 21 cm emission. The H$_i$ spatial distribution was obtained via a simple velocity integral over the line channels of the spectral cube; this directly provides the H$_i$ column density at different spatial locations. This was done for the cubes at resolutions of $7'' - 16''$. For the H$_i$ velocity field, we used a single resolution, $12'' \times 12''$, chosen to provide both good H$_i$ column density sensitivity and good angular resolution. We used a flux density threshold of 0.7$\sigma$ on the cube to exclude noise peaks, where $\sigma$ is the RMS noise on the cube per 10 km s$^{-1}$ channel. The threshold was applied after smoothing the cube both spatially (Gaussian kernel, of FWHM $\approx 1.5$ times the synthesized beam) and spectrally (Hanning smoothing, by 10 channels). The wide Hanning-smoothing kernel was used because the spectral features are both wide and weak. We emphasize that the smoothing was done only in order to create the mask for applying the thresholds.

3. RESULTS AND DISCUSSION

Fig. 1[A] shows the GMRT H$_i$ 21 cm spectrum of GP J0213+0056, obtained from our lowest-resolution (37'' × 32'') cube, at a velocity resolution of 10 km s$^{-1}$. The RMS noise on the spectrum is $\approx 1.0$ mJy per 10 km s$^{-1}$ channel, and the integrated H$_i$ 21 cm line flux density is $0.287 \pm 0.044$ Jy km s$^{-1}$. This yields an H$_i$ mass of $(2.34 \pm 0.36) \times 10^9$ M$_\odot$, marginally lower than, but formally consistent with, the value of $(3.17 \pm 0.17) \times 10^9$ M$_\odot$ obtained by Kanekar et al. (2021) from their GBT spectrum.

Fig. 2 shows images of the H$_i$ 21 cm emission in and around GP J0213+0056 at angular resolutions of [A] 16'', [B] 12'', [C] 9'', and [D] 7'', overlaid on a Subaru HypersuprimeCam (HSC) i-band image (Aihara et al. 2022) of the field. At the coarsest angular resolution of 16'', Fig. 2[A] shows that the Green Pea lies away from the peak of the H$_i$ 21 cm emission. At higher resolution, the H$_i$ 21 cm emission in panels [B] and [C] is seen to arise from a ring-like structure around the Green Pea; the H$_i$ distribution is clearly disturbed, indicating a merger system (e.g. Hibbard et al. 2001). We hence searched the SDSS for nearby companion galaxies, and identified a galaxy SDSS J021306.26+005609.9 (hereafter, G1) at $z = 0.0400$, just $\approx 5.7''$, i.e. $\approx 4.7$ kpc, to the south-west of GP J0213+0056 and at almost exactly the same redshift. The locations of the Green Pea and G1 are indicated in the four panels of Fig. 2. The galaxy G1 is clearly detected in the Subaru HSC image, which shows that both the Green Pea and G1 are highly distorted due to the merger.

Fig. 2 shows that GP J0213+0056 lies at the edge of the H$_i$ 21 cm emission, with no emission seen from the Green Pea location or immediately east of it in the highest-resolution images of [C] and [D]. The 3$\sigma$ upper limit on the H$_i$ column density at the Green Pea location is $\approx 3 \times 10^{20}$ cm$^{-2}$, from the 9''-resolution cube, at a velocity resolution of 10 km s$^{-1}$. Indeed, it is clear from Figs. 2[C] and [D] that the strongest H$_i$ 21 cm emission arises from neither the Green Pea nor G1, but from the
Figure 2. The H\textsubscript{i} spatial distribution around GP J0213+0056 (in contours), at resolutions of [A] 16″, [B] 12″, [C] 9″, and [D] 7″, each overlaid on the Subaru HSC i-band image. The GMRT synthesized beam FWHM is indicated by the circle on the bottom left of each panel. The contours in each panel are at \((-2.0, 2.0, 3.0, 4.0, 5.0) \times \sigma\), with the base contours at H\textsubscript{i} column densities of [A] $1.4 \times 10^{20}$ cm$^{-2}$, [B] $2.2 \times 10^{20}$ cm$^{-2}$, [C] $3.5 \times 10^{20}$ cm$^{-2}$, and [D] $5.3 \times 10^{20}$ cm$^{-2}$; negative values are shown with dashed contours. The locations of GP J0213+0056 and G1 are indicated in each panel by the label “GP” and the symbol “×”, respectively.

region around them. The highest H\textsubscript{i} column density in our H\textsubscript{21} cm images, $\approx 1.9 \times 10^{21}$ cm$^{-2}$ in the 7″-resolution image of [D], arises to the west of G1 and the Green Pea. The angular offset between the highest H\textsubscript{i} column density location and the centre of the galaxy G1 is $\approx 7.9″$, far larger than the positional accuracy of the GMRT images ($\lesssim 1.8″$, from the continuum image). As such, we rule out the possibility that the peak of the H\textsubscript{i} column density arises from G1.

McKinney et al. (2019) tentatively detect weak Ly\textalpha{} absorption in GP J0213+0056, around the much stronger Ly\textalpha{} emission, obtaining an H\textsubscript{i} column density of $(1.00 \pm 0.48) \times 10^{20}$ cm$^{-2}$. This is consistent with the observed H\textsubscript{i} distribution in Fig. 2, which indicates that the GP lies at the edge of the H\textsubscript{21} cm emission, with an H\textsubscript{i} column density $\lesssim 10^{20}$ cm$^{-2}$.

Fig. 3 shows the H\textsubscript{i} velocity field at an angular resolution of $12″ \times 12″$. A velocity gradient is visible in
GP J0213+0056 has revealed that the \( \text{H} \text{i} \) broken-ring structure, and evidence of disturbed kinematics, clear indications of merger activity. Consistent with the merger hypothesis, we have identified a main-sequence galaxy G1, \( z \approx 4.7 \) kpc away from GP J0213+0056 and at almost exactly the same redshift, \( z \approx 0.0400 \), with a slightly higher stellar mass.

GP J0213+0056 and G1 are identified as independent galaxies by the SDSS. However, the separation between the two is very small, \( \approx 4.7 \) kpc. It is possible that the Green Pea is a young super star-cluster formed in G1 during the major merger, i.e. that GP J0213+0056 and G1 are not distinct galaxies. It has been suggested that such super star-clusters can form efficiently in both high-\( z \) \( \text{Ly} \alpha \) -emitting galaxies (Elmegreen et al. 2012) and nearby dwarf starburst galaxies (Renaud 2018). However, we note that the estimated stellar mass of GP J0213+0056 is quite large, \( \approx 7.8 \times 10^8 \ M_\odot \), larger than expected for a super star-cluster within a galaxy.

GP J0213+0056 lies at the edge of the \( \text{H} \text{i} \) 21 cm emission seen in Figs. 2[B–D], with no \( \text{H} \text{i} \) 21 cm emission detected at the Green Pea location in the higher-resolution \( \text{H} \text{i} \) 21 cm images. This lack of \( \text{H} \text{i} \) 21 cm emission at the location of GP J0213+0056 suggests the presence of holes in the \( \text{H} \text{i} \) spatial distribution, due to the merger. Such holes in the \( \text{H} \text{i} \) distribution would facilitate the leakage of ionizing radiation from the Green Pea, consistent with the strong \( \text{Ly} \alpha \) emission detected by Jaskot et al. (2019), with a \( \text{Ly} \alpha \) escape fraction of \( \approx 12\% \). The
Table 2. Properties of GP J0213+0056. The columns are (1) the ratio of the luminosity in the [O\textsc{iii}]\(\lambda5007\)Å and [O\textsc{ii}]\(\lambda3727\)Å lines, O32 (Kanekar et al. 2021), (2) the equivalent width of the Ly\(\alpha\) line, in Å (Jaskot et al. 2019), (3) the Ly\(\alpha\) peak separation (Jaskot et al. 2017), (4) the Ly\(\alpha\) escape fraction (Jaskot et al. 2019), (5) the gas covering fraction (McKinney et al. 2019), (6) the stellar mass (Jiang et al. 2019), (7) the star formation rate (Jiang et al. 2019), and (8) the H\(\text{i}\) mass (this work).

| O32  | EW(Ly\(\alpha\)) | \(\Delta \nu_{\text{Ly}\alpha}\) | \(f_{\text{esc}}^{\text{Ly}\alpha}\) | \(f_{\text{cov}}\) | \(M_\star\) | SFR | \(M_{\text{HI}}\) |
|------|-----------------|----------------------|-----------------|-----------------|----------|-----|-----------|
| 8.8  | 42              | 397                  | 12%             | 0.54            | 7.8      | 1.4 | 2.34      |

major merger is likely to have both triggered the starburst in GP J0213+0056 and created the pathways by which Ly\(\alpha\), and possibly LyC, radiation could leak from the Green Pea galaxy.

Unlike other Green Peas at higher redshifts, \(z \approx 0.2\) (e.g. Izotov et al. 2018b,a), LyC emission has not so far been directly detected from GP J0213+0056. However, LyC escape in Green Pea galaxies has been shown to correlate with the O32 value, the gas covering fraction, and the Ly\(\alpha\) emission properties such as the line equivalent width (EW), the Ly\(\alpha\) line peak separation and Ly\(\alpha\) escape fraction (Izotov et al. 2016, 2018b; Jaskot et al. 2017, 2019), although no individual property provides a definitive indicator (e.g. Verhamme et al. 2017). The properties of GP J0213+0056 are listed in Table 2. The moderately high O32 value and Ly\(\alpha\) equivalent width, and the moderate gas covering fraction, all suggest the possibility of LyC leakage from GP J0213+0056. However, the Ly\(\alpha\) escape fraction of \(\approx 12\%\) is not very high and the separation between Ly\(\alpha\) emission peaks is large, both indicators of low LyC leakage. The current data are thus not conclusive on whether or not GP J0213+0056 is likely to be a LyC leaker.

4. SUMMARY

We have used the GMRT to map the H\(\text{i}\) 21 cm emission from GP J0213+0056 at \(z = 0.0399\), providing the first images of the spatial distribution of H\(\text{i}\) in and around a Green Pea galaxy. The GMRT images indicate that the starburst in GP J0213+0056 is likely to have been triggered as the result of a major merger with a companion galaxy, G1, just \(\approx 4.7\) kpc away, and with a stellar mass higher than that of the Green Pea. The H\(\text{i}\) 21 cm emission arises from a broken-ring structure around the Green Pea and G1, with no H\(\text{i}\) 21 cm emission detected at the location of GP J0213+0056 in the higher-resolution images. The strong Ly\(\alpha\) emission observed from GP J0213+0056 is likely to arise due to the escape of Ly\(\alpha\) and LyC photons through holes in the H\(\text{i}\) spatial distribution caused by the merger.

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