Discovery of an extremely gas rich dwarf triplet near the centre of the Lynx–Cancer void

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ABSTRACT

The Giant Metrewave Radio Telescope (GMRT) H\textsubscript{i} observations, done as part of an ongoing study of dwarf galaxies in the Lynx–Cancer void, resulted in the discovery of a triplet of extremely gas rich galaxies located near the centre of the void. The triplet members SDSS J0723\textdegree+3621, SDSS J0723\textdegree+3622 and SDSS J0723\textdegree+3624 have absolute magnitudes $M_B$ of $-14.2$, $-11.9$ and $-9.7$ and $M$(H\textsubscript{i})/L\textsubscript{B} of $\sim2.9$, $\sim10$ and $\sim25$, respectively. The gas mass fractions, as derived from the Sloan Digital Sky Survey (SDSS) photometry and the GMRT data, are 0.93, 0.997 and 0.997, respectively. The faintest member of this triplet, SDSS J0723\textdegree+3624, is one of the most gas rich galaxies known. We find that all three galaxies deviate significantly from the Tully–Fisher relation, but follow the baryonic Tully–Fisher relation. All three galaxies also have a baryon fraction that is significantly smaller than the cosmic baryon fraction. For the largest galaxy in the triplet, this is in contradiction to numerical simulations. The discovery of this very unique dwarf triplet lends further support to the idea that the void environment is conducive to the formation of galaxies with unusual properties. These observations provide further motivation to do deep searches of voids for a ‘hidden’ very gas rich galaxy population with $M_B \gtrsim -11$.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: kinematics and dynamics – large-scale structure of Universe – radio lines: galaxies.

1 INTRODUCTION

Early redshift surveys established that the spatial distribution of bright galaxies is highly inhomogeneous and that the properties of the galaxy population vary with environment. The spatial distribution was found to consist of large underdense regions (‘voids’) surrounded by galaxies in sheets and walls (Jöveer, Einasto & Tago 1978; Kirshner et al. 1981; Geller & Huchra 1989). Further, the morphological mix of galaxies was found to vary systematically with galaxy density. The fraction of late-type galaxies monotonically increases as one goes from high-density to low-density regions (Postman & Geller 1984). Subsequent numerical simulations showed that the existence of voids can be understood as a consequence of biasing in the formation of galaxy haloes, with the most massive haloes being formed in regions of high densities (White et al. 1987). However, numerical simulations also predicted that the voids should be filled with small mass haloes (e.g. Davis et al. 1985; Gottlöber et al. 2003). Peebles (2001) pointed out that, contrary to this expectation, the known dwarf galaxies instead follow the same large-scale distribution as the bright galaxies, a discrepancy that he dubbed the ‘void phenomenon’. We note that earlier (Pustilnik et al. 1995) as well as recent (Kreckel et al. 2012) studies do find dwarf galaxies inside voids; however, it remains true that the brighter dwarfs generally lie near the void walls. Peebles (2001) also highlighted that if the small dark haloes produced in voids preferentially fail to host galaxies, this would correspond to a discontinuous change in galaxy properties with density. This distinguishes the ‘void phenomenon’ from the observed ‘morphology–density’ relationship in which the morphological mix varies smoothly with density. Observational and theoretical studies of the void galaxy population have since been largely focused on these two (possibly related) issues, namely (i) a search for the ‘missing’ dwarfs in voids and (ii) the influence of the large-scale environment on galaxy properties.

Regarding the issue of missing dwarfs, deep searches of voids have shown that they do not contain dwarf galaxies in the numbers predicted by simulations (see e.g. Tikhonov & Klypin 2009; Kreckel 2012).
et al. 2012). The reason for this discrepancy is unclear, although there have been numerous suggestions that the formation of galaxies in small dark matter haloes in voids is suppressed (e.g. Tinker & Conroy 2009; see also Kreckel, Joung & Cen 2011). Essentially, if small haloes in voids are baryon deficient, this would resolve the problem of missing dwarfs. Hoefl & Gottlöber (2010) examined the baryon fraction of small haloes in both voids and filaments using high-resolution simulations, and found no dependence of the baryon deficiency on environment. The discrepancy between numerical simulations and the observations hence remains a puzzle.

Regarding the issue of the effect of the large-scale environment on the properties of void galaxies, studies using Sloan Digital Sky Survey (SDSS) selected samples established that the void galaxy population is significantly bluer and has a higher star formation rate as compared to the high-density galaxy population (Rojas et al. 2004, 2005). However, Patiri et al. (2006; see also Park et al. 2007) show that this difference is almost entirely due to the morphology–density relation. Late-type galaxies, which are more dominant in low-density regions, have bluer colours and higher star formation rates than early-type galaxies. At a fixed luminosity and morphology, the properties of the detected void galaxies are statistically identical to that of galaxies in dense regions. It is worth noting here that these conclusions relate only to the upper part of the whole luminosity (or mass) range of void galaxies ($M_B$ > $-16$ mag) and do not include study of possible differences in parameters such as the gas phase metallicity and gas mass fraction.

The gas mass fraction of void galaxies was studied in earlier works which looked at the distribution of $M(H\alpha)/L_B$. Huchtmeier, Hopp & Kuhn (1997) found that dwarf galaxies closer to the centre of the void had a higher $M(H\alpha)/L_B$ than galaxies close to the walls. Similarly, Pustilnik et al. (2002) found marginal evidence for low-luminosity galaxies in voids to have a higher $M(H\alpha)/L_B$ than those in higher density regions. Extrapolation of the obtained trends to the range $M_B$ > $-15$ indicated that for lower mass dwarfs the difference could be higher. On the other hand, Kreckel et al. (2012) show that the $H\alpha$ gas content of void galaxies are statistically indistinguishable from galaxies in filaments and walls, at least for galaxies brighter than $M_B$ > $-16$ mag. This result does not contradict earlier results, and underlines the need of deeper void galaxy samples (VGSs).

A possible resolution of the discrepancy between the predictions of the numerical simulations and the observations is that the dwarfs predicted to exist in voids are fainter than what the observations have probed so far. For example, in their simulation, Kreckel et al. (2011) find that while luminous dwarfs ($M_B$ brighter than $-18$ mag) in voids are statistically indistinguishable from similar dwarfs in higher density regions, fainter dwarfs ($M_B$ > $-16$ mag) are significantly bluer and have higher specific star formation rates than their higher density counterparts. They also find a significant excess of faint dwarf ($M_B$ > $-14$ mag) galaxies that are preferentially located in low-density regions near the void centre. To complement their numerical simulations, Kreckel et al. (2012) used the SDSS to identify a population of void galaxies with $M_B$ > $-16.1$ mag. To identify and study still fainter objects, one needs to focus on the nearby voids.

In a recent series of papers (Pustilnik & Tepliakova 2011, hereafter Paper I; Pustilnik et al. 2011b, hereafter Paper II; Pustilnik et al. 2011a, hereafter Paper III), a sample of 79 galaxies residing in the nearby Lynx–Cancer void was presented. The sample galaxies have $M_B$ down to $-12$ mag, with reasonable completeness level at $M_B$ > $-14.0$ mag. For this completeness level, the average void galaxy density ($\sim 0.04$ Mpc$^{-3}$) is about one order of magnitude smaller than the mean value for the faint SDSS galaxies derived by Blanton et al. (2005). More than half of the Lynx–Cancer void sample consists of low surface brightness dwarfs (LSBDs). Measurements of O/H are available for $\sim 60$ per cent of the sample, and shows that the metallicity of the void galaxies is on average $\sim 30$ per cent lower than that of their counterparts in denser regions. About 10 per cent of the sample are deficient in metals by factors of 2–7. A Giant Metrewave Radio Telescope (GMRT) based $H\alpha$ study of these dwarfs is in progress. Here we report on a highly unusual system found in the course of the $H\alpha$ observations, namely an extremely gas rich triplet of LSBD galaxies, located inside the central 10 per cent of the void volume.

### Table 1. Parameters of the GMRT observations.

| J0723+36 triplet |
|------------------|
| Date of observations | 2011 Nov 25 |
| Field centre RA (2000) | 07°23′50″0 |
| Field centre Dec. (2000) | +36°22′41″0 |
| Central velocity (km s$^{-1}$) | 950.0 |
| Time on-source (h) | $\sim 6$ |
| Number of channels | 256 |
| Channel separation (km s$^{-1}$) | $\sim 1.73$ |
| Flux calibrators | 3C 48, 3C 286 |
| Phase calibrators | 0741+312 |
| Resolution (arcsec$^2$) | 40 × 40 |
| rms (mJy beam$^{-1}$) | 2.8 |

### 2 OBSERVATIONS AND RESULTS

The GMRT $H\alpha$ 21-cm observations of the J0723+36 system were conducted on 2011 November 25. The observational parameters are given in Table 1. The initial flagging and calibration was done using the *FLAGCAL* package (Prasad & Chengalur 2012) and further processing was done using standard tasks in the *AIPS* package. The hybrid resolution of the GMRT allows one to make maps at various resolutions; however, here we show only maps at 40-arcsec resolution.

In the top panel of Fig. 1 is shown the GMRT $H\alpha$ map of the J0723+36 system. At the time of the observations, only two galaxies, namely SDSS J0723+3621 and SDSS J0723+3622, were known to lie within the observed data cube. At the adopted distance of 16 Mpc (see below) to this group, the separation of the pair is 12.1 kpc. As can be seen from the figure, the GMRT observations detected one more $H\alpha$ source, which corresponds to the galaxy SDSS J0723+3624. The projected separation between this companion and the brighter of the two galaxies in the pair (namely J0723+3621) is 23.9 kpc. SDSS g-band images showing these galaxies is shown in Figs 2 and 3 (a colour composite for this pair is also shown in Paper III). The two brighter galaxies, J0723+3621 and J0723+3622, are clearly interacting, with a bridge of $H\alpha$ connecting them. For the third, much smaller system, there is a hint of an extension to the north-west, but the resolution is marginal. The velocity field (with isovelocity lines in steps of $6.0$ km s$^{-1}$ for the whole system is shown in Fig. 1 (bottom panel). All three galaxies show clear velocity gradients, although in all cases the velocity field is disturbed. In the case of the galaxy pair, this is clearly due to the ongoing tidal interaction. The spins of both components of the pair are aligned with their orbital angular momentum, consistent with the pair undergoing a prograde collision. A prograde encounter geometry is also consistent with the significant tidal distortions seen.
Gas rich dwarfs in the Lynx–Cancer void

Figure 1. Top panel: the integrated H\textsc{i} emission (moment0 map) from the J0723+36 system. The angular resolution is 40 arcsec. The contours start at $3 \times 10^{19}$ atoms cm$^{-2}$ and are in steps of 1.414. Bottom panel: the velocity field (moment1 map) of the J0723+36 system, derived from the 40-arcsec resolution data. The isovelocity contours start at 870.0 km s$^{-1}$ and are in steps of 6 km s$^{-1}$.

A continuum image made using all the available channels shows no emission from the triplet galaxies. The rms noise level is $\sim0.5$ mJy beam$^{-1}$ at an angular resolution of 40 arcsec.

The main parameters of the three galaxies in the J0723+36 system are given in Table 2. The H\textsc{i} parameters are derived from the integrated single-dish profiles shown in Fig 4. Because the velocity fields are disturbed, we do not attempt to derive rotation curves. Instead, we use the velocity widths obtained from the integrated profiles to estimate the dynamical mass-related quantities. The optical parameters are derived from the SDSS Data Release 7 (DR7) data (Abazajian et al. 2009). In the case of the newly discovered companion galaxy J0723+3624, there are two extended SDSS objects, separated by $\sim5.5$ arcsec (0.4 kpc in projection) seen near the centre of the H\textsc{i} emission. We refer below to these two objects associated with the companion J0723+3624 as the north-east (NE) and south-west (SW) components. The NE component (J072320.57+362440.8) has $g = 21.42$ and somewhat blue colours $[(g - r)_{0} = 0.09 \pm 0.19]$, albeit with large error bars. Independent photometry of this object based on the SDSS images resulted in very similar values, namely $g = 21.29 \pm 0.05$ and $(g - r)_{0} = 0.08 \pm 0.08$. The SW component J072320.32+362436.7 is $\sim1.3$ mag fainter in $g$ filter and is significantly redder $[(g - r)_{0} = 0.63 \pm 0.28]$. Independent measurements from the SDSS data once again result in similar values, namely a $g$ flux that is $\sim1.2$ mag fainter and $(g - r)_{0} = 0.60 \pm 0.11$. This ‘red nebulosity’ looks similar to the very faint red galaxies seen to the north and east of the blue component, which could represent a small group of distant galaxies. We hence assume that the red nebulosity is unrelated to the H\textsc{i} cloud. In any case, including this component would make only a minor difference to the total flux – making the object brighter in the $B$ band by 0.26 mag.

The rows of Table 2 are as follows. Rows 1 and 2: the J2000 RA and Dec.; row 3: $A_{B}$, the Galactic extinction in $B$ band; row 4: the total $B$ magnitude, not corrected for $A_{B}$, obtained by transformation from the total $g$ and $r$, according to the formulae given in Lupton (2005); row 5: the $(g - r)$ colour; row 6: the $(B - V)$ colour, computed from the observed $(g - r)$ and for the PEGASE2 constant

Figure 2. The SDSS $g$-band image showing the two main galaxies in the triplet, namely J0723+3621 (the edge-on galaxy) and J0723+3622 (the fainter companion).

Figure 3. The SDSS $g$-band image showing the faintest member of the triplet, J0723+3624. The GMRT H\textsc{i} contours are also overlaid, the contour levels are the same as in Fig. 1.
Table 2. Main parameters of the J0723+36 triplet.

| Parameter         | J0723+3621 | J0723+3622 | J0723+3624 |
|-------------------|------------|------------|------------|
| RA (J2000.0)      | 07 23 01.42 | 07 23 13.46 | 07 23 20.57 |
| Dec. (J2000.0)    | +36 21 17.1 | +36 22 13.0 | +36 24 40.8 |
| Av (from NED)     | 0.23       | 0.23       | 0.23       |
| Btot              | 17.01 ± 0.03 | 19.31 ± 0.03 | 21.56      |
| (g − r)0, tot     | 0.34 ± 0.01 | −0.12 ± 0.11 | 0.08 ± 0.12 |
| (B − V)0, tot     | 0.34 ± 0.01 | 0.02 ± 0.08  | 0.17 ± 0.09 |
| Vhel(Hi) (km s⁻¹) | 917 ± 1     | 970 ± 1     | 938 ± 1    |
| Distance (Mpc)    | 16.0        | 16.0        | 16.0        |
| Mdyn (M☉)         | 359.5       | 102.3       | 16.9        |
| Mvir (M☉)         | 0.23        | 0.23        | 0.23        |
| H₁ int. flux (Jy km⁻¹) | 3.74 ± 0.4   | 1.59 ± 0.2  | 0.48 ± 0.05 |
| W₂₀ (km s⁻¹)      | 100.2 ± 0.7 | 45.3 ± 0.7  | 22.0 ± 0.7  |
| W₀₂ (km s⁻¹)      | 122.5 ± 1.0 | 69.0 ± 1.0  | 33.5 ± 1.0  |
| i (°)             | 90:         | 60:         | 60:         |
| M(Hi) (×10⁷ M☉)   | 22.6        | 9.61        | 2.9         |
| Mbary (×10⁷ M☉)   | 32.37       | 12.8        | 3.86        |
| Mdyn (×10⁷ M☉)    | 623.8       | 132.5       | 16.91       |
| Mvir (×10⁷ M☉)    | 359.5       | 102.3       | 8.9         |
| R₂₂ (kpc)         | 87.3        | 57.4        | 25.4        |
| M(Hi)/L₂₂         | 2.9         | 10.2        | 25          |
| fgas              | 0.93        | 0.997       | 0.997       |
| fbary             | 0.009       | 0.013       | 0.043       |

As can be seen from Table 2, all three galaxies have very large M(Hi)/L₂₂ ratios; in fact, J0723+3624 has one of the largest ratios known. The corresponding gas mass fractions are also extremely large. Even if we assume that the colours of J0723+3622 and J0723+3624 are redder by 1σ than the measured values, their gas mass fractions remain >0.99. For star-forming galaxies, the gas mass fraction is known to increase with decreasing luminosity (see e.g. McGaugh & de Blok 1997; Geha et al. 2006). We show in Fig. 5 M(Hi)/L₂₂ for the FIGGS (Begum et al. 2008b) sample, which also clearly shows this trend. The data for the galaxies from the J0723+36 triplet are also shown, and, as can be seen, for their given luminosities, all three galaxies lie at the extreme gas-rich end of the distribution.

We also compare the galaxies’ location in the Tully–Fisher (TF) and baryonic Tully–Fisher (BTF) diagrams. We note that the inclinations estimated for these galaxies are somewhat uncertain; however, this should affect the TF and BTF relations equally. In Fig. 6 (left-hand panel) is shown the TF relation for the FIGGS galaxies. Also overplotted is the TF relation for bright galaxies, as determined by Tully & Pierce (2000). As expected for dwarf galaxies, the FIGGS galaxies are underluminous for their velocity width (see also Begum et al. 2008a). Once again, the triplet galaxies fall at the extreme end of the distribution. Fig. 6 (right-hand panel) shows the BTF relation, with the BTF relation from De Rijcke et al. (2007) given in Zibetti, Charlot & Rix (2009) (similar to that used in Paper III).
figure 5. Comparison of the \( \frac{M(H)I}{L_B} \) ratio of the galaxies in the Lynx–Cancer triplet (filled squares), with galaxies from the FIGGS sample (× symbols; Begum et al. 2008b). Three very gas rich dwarfs from the VGS of Kreckel et al. (2012) are shown as circles, and data for six other extremely gas rich galaxies (see Table 3) are shown in triangles. The solid line is the best-fitting relation for the FIGGS galaxies.

shown for reference. Despite being extremely gas rich, the triplet galaxies do follow the BTF relation.

The baryon fraction of small galaxies is also an interesting quantity to compare against model predictions. For our extremely gas rich galaxies, the baryon fraction can be accurately measured. From numerical models (Hoeft et al. 2006; Hoeft & Gottlöber 2010), one would expect that galaxies with circular velocities \( \gtrsim 50 \text{ km s}^{-1} \) would have a baryon fraction equal to that of the cosmic value of \( \sim 0.17 \) (Jarosik et al. 2011). For smaller galaxies, the baryon fraction drops sharply with circular velocity, at a circular velocity of \( 20 \text{ km s}^{-1} \); the predicted baryon fraction is an order of magnitude below the cosmic value. As can be seen from Table 2, for all galaxies the baryon fraction \( f_{\text{bar}} \) is more than an order of magnitude lower than the cosmic baryon fraction. In the case of the brightest galaxy J0723+3621, the baryon fraction is \( \sim 1/20 \) of the cosmic baryon fraction, while one would expect it to have the cosmic baryon fraction. This galaxy is clearly edge-on, and this result is hence unlikely to be due to an uncertain inclination angle. McGaugh et al. (2010) has earlier highlighted that the measured baryon fraction for galaxies with rotation velocities in this range is significantly smaller than the cosmic baryon fraction. In this respect, J0723+3621 is similar to dwarf galaxies located outside of voids. Interestingly, \( f_{\text{bar}} \) appears to decrease with increasing velocity width, i.e. the reverse of what is predicted. One possible reason for this could be that for the smaller galaxies the baryons do not sample the flat part of the rotation curve, and hence \( W_{20} \) underestimates the circular velocity. It is also worth noting that the expected virial radius of even the smallest galaxies’ dark matter halo is larger than the separation of the galaxies in this triplet. If one regards the entire triplet as a single system, then the \( f_{\text{bar}} \) is \( \sim 0.01 \), about 16 times smaller than that of the cosmic baryon fraction.

The triplet of galaxies that we are discussing here are found in the inner 10 per cent volume of the Lynx–Cancer void. Kreckel et al. (2012) also find three similarly gas-rich galaxies (VGS_7a, VGS_9a and VGS_12) in their void survey. Their absolute blue magnitudes computed from the SDSS magnitudes following the same procedures as for our triplet galaxies are \( M_B \) of \( -13.86, -11.17 \) and \( -16.49 \), respectively. The corresponding \( \frac{M(H)I}{L_B} \) ratios are \( \sim 5.9, \sim 12.5 \) and \( \sim 4.9 \). These very gas rich galaxies found in surveys of voids are interesting in view of the possibility highlighted by Peebles (2001) that the void environment could be conducive to the production of galaxies with extreme properties.

To examine this issue further, we take a look at the 11 galaxies with well-measured \( \frac{M(H)I}{L_B} \gtrsim 5 \) that we are aware of. The sample consists of three galaxies from the Kreckel et al. (2012) VGS sample, the two fainter members of the triplet discussed in this paper and six galaxies taken from the literature (see Table 3).
For the two members of Lynx–Cancer void triplet and three most
gas rich VGS galaxies, the type of global environment is clear from
the sample selection. For the six galaxies from Table 3, the envir-
onment varies. The nearest two objects, UGC 292 and DDO 154,
are situated on the periphery of the loose aggregate named Canis
Venatici I Cloud (Karachentsev et al. 2003), which probably is still
in the formation phase. The next most distant galaxy And IV is
situated far from luminous galaxies, at $D \sim 6.1$ Mpc, and accord-
ing to Ferguson, Gallagher & Wise (2000) probably belongs to a
loose dwarf group. However, its projected distances to the bright-
est dwarfs of this group are of more than 2 Mpc. The distance to
the unusual pair of very gas rich objects HI 1225+01 SW and HI 1225+01 NE
is very uncertain, since it is unclear if this object lies in the foreground or background of the Virgo cluster. Because of
this distance uncertainty, it is not possible to make a definitive
statement about its environment. However, after a detailed analy-
ysis, Salzer (1992) conclude that there is no evidence for a massive
neighbour within $\sim 1$ Mpc of the system. The SBS 0335–052 sys-
tem is at a projected separation of only 150 kpc from the large
spiral galaxy NGC 1376 (Pustilnik et al. 2001). Peebles (2000)
examined its location with respect to galaxies from the ORS (Santiago et al. 1995), and concluded that while it is not located in a dense region, neither is it located in a void. In summary, while all of the gas-rich galaxies appear relatively isolated, it is not the case that they are all
located deep inside voids.

Next, we use star formation models to constrain the evolutionary
history of these extremely gas rich galaxies. For five of these galax-
ies, we only have the $(B-V)$ colour available, and we hence use
this colour to constrain the star formation history. Unfortunately,
due to the degeneracy of the evolutionary tracks for continuous and
instantaneous star formation laws in $B-V$, $V-R$ diagrams, one
cannot distinguish between $\sim 3$ Gyr old constant star formation rate
and $\sim 1$ Gyr old burst. Including $u$ or $U$ band data in the analysis
allows one in many cases to do this. For example, Pustilnik et al.
(2008, 2010) and Paper II use SDSS $u$, $g$, $r$ colours for similar
gas-rich metal-poor blue galaxies to show that in most cases a con-
stant star formation law is preferable. Assuming that the LSB
galaxies in the current sample have been forming stars at a con-
stant rate, we used PEGASE2 models to compute the dependence of
$M(H\beta)/L_B$ and the $B-V$ colour on the age of the galaxy. We show in

\begin{table}[h]
\centering
\caption{Main parameters of galaxies with the highest $M(H\beta)/L_B$ ratios.}
\begin{tabular}{lcccccc}
\hline
Parameter & And IV & SBS 0335–052 & HI 1225+01 SW & HI 1225+01 NE & UGCA 292 & DDO 154
\hline
RA (J2000.0) & 00 42 32.30 & 03 37 38.40 & 12 26 55.00 & 12 27 46.29 & 12 38 44.63 & 12 54 05.20
Dec. (J2000.0) & 00 34 18.7 & -05 02 36.4 & +01 24 35.0 & +01 35 57.1 & +32 45 01.5 & +27 08 59.0
$B_{tot}$ & 16.56 & 19.14 & – & 16.0 & 16.10 & 13.94
$V_{hel}(H\beta)$ (km s$^{-1}$) & 234 & 4017 & 1226 & 1299 & 308 & 374
Distance (Mpc) & 6.1 & 53.6 & 20.0 & 20.0 & 3.61 & 4.0
$M_B^0$ & $-12.6$ & $-14.70$ & $>-11.5$ & $-15.49$ & $-11.76$ & $-14.13$
$(B-V)^0$ & 0.20 & -0.12 & $>-0.10$ & -0.10 & 0.08 & 0.18
$\mu_B^0$ (mag arcsec$^{-2}$) & 23.3 & 22.5 & 27.3 & 23.1 & 27.4 & 23.2
$12+\log(O/H)$ & 7.50 & 7.00 & 7.63 & 7.30 & 7.54 & 7.54
HI int. flux (Jy km$^{-1}$) & 18.0 & 0.86 & 9.1 & 23.1 & 17.6 & 82.1
$M(H\beta)/(10^7M_\odot)$ & 15.8 & 58.3 & 86 & 220 & 5.4 & 31.0
$M(H\beta)/L_B$ & 13.0 & 4.9 & $>155$ & 10.1 & 6.93 & 4.52
$f_{gas}$ & 0.99 & 0.995 & $>0.999$ & 0.993 & 0.993 & 0.997
\hline
\multicolumn{7}{l}{\textsuperscript{a}From NED; \textsuperscript{b}data for And IV: Ferguson et al. (2000); Chengalur et al. (2008); Pustilnik et al. (2008); Pramskij & Kniazev (2004); Eka, Pustilnik & Chengalur (2009); Izotov et al. (2009); \textsuperscript{c}data for SBS 0335–052W: Pustilnik, Pramskij & Kniazev (2004); Eka, Pustilnik & Chengalur (2009); Izotov et al. (2009); \textsuperscript{d}data for HI 1225+01 SW and HI 1225+01 NE: Salzer et al. (1991); Chengalur, Giovannelli & Haynes (1995); Turner & MacFadyen (1997); we adopt $D = 20$ Mpc, while $\sim 10$ and $\sim 15$ Mpc are possible alternatives; \textsuperscript{e}data for UGCA 292: van Zee (2000); Makarova et al. (1998); \textsuperscript{f}data for DDO 154: Carignan & Freeman (1988); Carignan & Beaulieu (1989); Walter et al. (2008) (THINGS), O/H from Moustakas et al. (2010).}
\end{tabular}
\end{table}

Fig. 7 a grid of models with $f_{gas}=0.5, 0.8, 0.9, 0.95, 0.98$ and 0.99, and star formation which started 0.5, 1, 3, 5 and 12 Gyr ago. Consistent with the mass-to-light ratios that we have adopted in Table 2, one can see that models with $f_{gas} \lesssim 0.95$ do not match the observed $M(H\beta)/L_B$ and $B-V$ colours. Further, for the ‘blue’ colours ($B-V < +0.25$), typical of the gas-rich LSBDs considered here, the corres-
ponding ages are $<3$ Gyr. The conclusion is that for a continuous
star formation law, all such blue gas-rich galaxies should have $f_{gas} \lesssim 0.98$ and should have started their star formation relatively recently. These implied young ages are consistent with the conclusions of Pustilnik et al. (2008, 2010) and Paper II that the bulk of stellar
populations in several very metal poor dwarfs in the Lynx–Cancer
void is relatively young.
Gas rich dwarfs in the Lynx–Cancer void

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REFERENCES

Abazajian K. N. et al., 2009, ApJS, 182, 543
Begum A., Chengalur J. N., Karachentsev I. D., Shapley A., 2008a, MNRAS, 386, 138
Begum A., Chengalur J. N., Karachentsev I. D., Shapley A., Kaisin S., 2008b, MNRAS, 386, 1667
Blanton M. B., Lupton R., Schlegel D. J., Strauss M. A., Brinkmann J., Fukugita M., Loveday J., 2005, ApJ, 631, 208
Carignan C., Beaulieu S., 1989, ApJ, 347, 760
Carignan C., Freeman K. C., 1988, ApJ, 332, L33
Chengalur J. N., Giovanelli R., Haynes M. P., 1995, AJ, 109, 2415
Chengalur J. N., Begum A., Karachentsev I. D., Shapley A., Kaisin S., 2008, in Koribalski B. S., Jerjen H., eds, Astrophysics and Space Science Proceedings: Galaxies in the Local Volume. Springer, Netherlands, ISBN 978-1-4020-6932-1, p. 65
Davis M., Frenk C. S., White S. D. M., 1985, ApJ, 292, 371
De Rijcke S., Zeilinger W. W., Hau K. T., Prugniel P., Dejonghe H., 2007, ApJ, 659, 1172
Ekta B., Pustilnik S. A., Chengalur J. N., 2009, MNRAS, 397, 963
Ferguson A. M. N., Gallagher J. S., Wise R. F. G., 2000, AJ, 120, 821
Geha M., Blanton M. R., Masjedi M., West A. A., 2006, ApJ, 653, 240
Geller M. J., Huchra J. P., 1989, Sci, 246, 897
Gottlöber S., Lokas E. L., Klypin A., Hoffman Y., 2003, MNRAS, 344, 715
Haynes M. P. et al., 2011, AJ, 142, 170
Hoeft M., Gottlöber S., 2010, Adv. Astron., 2010, 16
Hoeft M., Yepes G., Gottlöber S., Springel V., 2006, MNRAS, 371, 401
Huchmeier W. K., Hopp U., Kuhn B., 1997, A&A, 319, 67
Izotov Y. I., Guseva N. G., Fricke K. J., Papaderos P., 2009, A&A, 503, 61
Jarosik N. et al., 2011, ApJS, 192, 14
Jöeveer M., Einasto J., Tago E., 2008b, MNRAS, 185, 357
Karachentsev I. D. et al., 2003, A&A, 398, 467
Kirshner R. P., Oemler A., Jr, Schechter P. L., Shectman S. A., 1981, ApJ, 248, L57
Kreckel K., Cen R., 2011, ApJ, 735, 132
Kreckel K., Platen E., Aragon-Calvo M. A., van Gorkom J. H., de Wijgaert R., van der Hulst J. M., Beguy B., 2012, AJ, 144, 16
Lupton R., 2005, http://www.sdss.org/dr5/algorithms/sdssUBVRITransform.html#Lupton2005
McGaugh S. S., de Blok W. J. G., 1997, ApJ, 481, 689
McGaugh S. S., Schombert M. J., de Blok W. J. G., Zavgren M. J., 2010, ApJ, 708, L14
Makarova L., Karachentsev I., Takalo L. O., Hein P., 2011, MNRAS, 415, 1188
Moustakas J., Kennicutt R. C., Tremonti C. A., Smith J.-D. T., Calzetti D., 2010, ApJS, 190, 233
Park C. et al. (SDSS Collaboration), 2007, ApJ, 658, 898
Patiri S. G., Prada F., Holtzman J., Klypin A., Betancort-Rijo J., 2006, MNRAS, 372, 1710
Peebles P. J. E., 2001, ApJ, 557, 459
Postman M., Geller M. J., 1984, ApJ, 281, 95
Prasad J., Chengalur J., 2012, Exp. Astron., 33, 157
Pustilnik S. A., Teplitakova A. L., 2011, MNRAS, 415, 1188
Pustilnik S. A., Ugryumov A. V., Lipovetsky V. A., Thuan T. X., Guseva N. G., 1995, ApJ, 443, 499

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As discussed in Section 1, one possible solution to the discrepancy between the number of dwarfs predicted by numerical solutions and the observed number of dwarfs in voids is that the void dwarfs are fainter than the faintest levels probed by the current surveys. The ongoing blind H I survey ALFALFA (Haynes et al. 2011) has a significantly higher sensitivity and angular resolution than previous surveys. However, even in the ALFALFA survey, objects like the faintest member of our triplet would be difficult to detect outside the local volume, J0723+3624 with \( F(H\alpha) = 0.48 \text{ Jy km s}^{-1} \) would fall below the survey detection limit were it to be placed \( \sim 1.5 \) times further than its current distance. ALFALFA is hence best placed to find galaxies such as this in voids with \( D_{\text{cent}} \lesssim 20 \text{ Mpc} \). Detection of substructure in systems like this triplet would, however, require follow-up synthesis imaging observations. We note in this context that Kreckel et al. (2012) find that void dwarfs show similar small-scale clustering as dwarfs in denser environments. For distances \( D > 16 \text{ Mpc} \) (distance moduli \( \mu > 34 \text{ mag} \)), these faint LSBs with \( B_{\text{maj}} > 19 \) will not be easily identified, either via blind H I surveys or via recently conducted wide-field spectral surveys, like the SDSS or 2dFGRS (Colless et al. 2001). The existence in voids of a population of very gas rich LSB dwarfs with \( M_B \lesssim -11 \) which escaped detection in previous studies, hence remains a viable option. Systematic searches for such faint dwarfs will require the next-generation optical and radio surveys.

4 SUMMARY AND CONCLUSIONS

In summary, we report the discovery of an extremely gas rich triplet of galaxies near the centre of the nearby Lynx–Cancer void. The triplet consists of the LSB galaxies J0723+3621 (\( M_B = -14.2 \)), J0723+3622 (\( M_B = -11.9 \)) and J0723+3624 (\( M_B = -9.7 \)) which lie within a projected separation of \( \sim 25 \text{ kpc} \) and a radial velocity interval of \( \sim 55 \text{ km s}^{-1} \). The \( M(H\alpha)/L_B \) ratios are \( \sim 2.9 \), 10 and 25, respectively. All of the galaxies lie at the extreme gas-rich end of the dwarf galaxy population. The faintest galaxy in the triplet J0723+3624 is one of the most gas rich galaxies known. The large \( M(H\alpha)/L_B \) and blue colours of the fainter two members of this triplet are consistent with star formation that started relatively recently (\( \lesssim 3 \text{ Gyr} \) ago). All three galaxies deviate significantly from the TF relation, but follow the BTF relation. For these extremely gas rich galaxies, the baryonic mass can be accurately determined. We find that the baryon fraction [computed assuming they have dark matter haloes with structures as predicted by Λ cold dark matter (ΛCDM) models] of all of the galaxies is significantly smaller than the cosmic baryon fraction. For the largest galaxy in the triplet, this is in contradiction to numerical simulations which predict that it should have a baryon fraction comparable to the cosmic mean value. The discovery of this very unusual dwarf triplet, along with the recent discovery by Kreckel et al. (2012) of other faint gas-rich dwarfs in voids, lends support to the suggestion that the void environment is a fertile hunting ground for unusual, less evolved, galaxies, which in many ways resemble high-redshift young galaxies.
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