Kinematics of dwarf galaxies in gas-rich groups, and the survival and detectability of tidal dwarf galaxies

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ABSTRACT
We present DEIMOS multi-object spectroscopy (MOS) of 22 star-forming dwarf galaxies located in four gas-rich groups, including six newly discovered dwarfs. Two of the galaxies are strong tidal dwarf galaxy (TDG) candidates based on our luminosity–metallicity relation definition. We model the rotation curves of these galaxies. Our sample shows low mass-to-light ratios (M/L = 0.73 ± 0.39 M⊙/L⊙) as expected for young, star-forming dwarfs. One of the galaxies in our sample has an apparently strongly falling rotation curve, reaching zero rotational velocity outside the turnover radius of rturn = 1.2re. This may be (1) a polar ring galaxy, with a tilted bar within a face-on disc; (2) a kinematic warp. These scenarios are indistinguishable with our current data due to limitations of slit alignment inherent to MOS-mode observations. We consider whether TDGs can be detected based on their tidal radius, beyond which tidal stripping removes kinematic tracers such as Hα emission. When the tidal radius is less than about twice the turnover radius, the expected falling rotation curve cannot be reliably measured. This is problematic for as much as half of our sample, and indeed more generally, galaxies in groups like these. Further to this, the Hα light that remains must be sufficiently bright to be detected; this is only the case for three (14 per cent) galaxies in our sample. We conclude that the falling rotation curves expected of TDGs are intrinsically difficult to detect.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: groups: general – galaxies: interactions – galaxies: kinematics and dynamics – dark matter.

1 INTRODUCTION
Occupying the low-mass end of the galaxy mass function, dwarf galaxies are more numerous than their giant counterparts (e.g. Bell et al. 2003; Oppenheimer et al. 2010), and as such can be an important tracer of environmental effects (e.g. Drinkwater et al. 2003). Moreover, the contribution by dwarf galaxies to hierarchical assembly and accretion on to giant galaxies is a vital part of our understanding of galaxy formation (e.g. Searle & Zinn 1978, and many observational and theoretical works since). In Λ cold dark matter (CDM) cosmology, galaxies form in haloes of CDM (Peebles 1965; Press & Schechter 1974; Blumenthal et al. 1984). These galaxies assemble into larger galaxies within still-larger haloes, which contribute a high M/L ratio and flat rotation curve for all galaxy masses (e.g. Navarro 1998; Klypin, Zhao & Somerville 2002). At the same time, continual enrichment of the interstellar medium means that larger galaxies have higher metallicities (e.g. Lequeux et al. 1979; Tremonti et al. 2004).

Galaxy groups are ideal laboratories for the study of dwarf galaxies, as it is at this density that the environment begins to contribute to their evolution. Moreover, the harsh conditions caused by galaxy clusters are not present, so that galaxy harassment is less frequent (Lewis et al. 2002; Gómez et al. 2003). Interactions between giant galaxies in such groups can cause the necessary Jeans instabilities for small galaxies to form in the tidal debris (Bournaud 2010). These so-called tidal dwarf galaxies (TDGs) share the high metallicity of the giant galaxies from which they formed, so are unusually metal-rich for their small size (e.g. Mirabel, Dottori & Lutz 1992; Duc et al. 2000; Weilbacher, Duc & Fritz-v. Alvensleben 2003). They also have no or little non-baryonic DM, though may contain a significant fraction of baryonic DM (Bournaud et al. 2007). Notwithstanding, they have a low M/L ratio (e.g. Braine et al. 2001) and are expected to have a falling, mass-follows-light rotation curve (e.g. Bournaud 2010; Duc et al. 2014). Understanding the fraction of dwarf galaxies that form in a tidal manner instead of in the...
traditional hierarchical assembly paradigm is crucial to instructing
cosmological simulations.

Most TDGs discovered to date have been detected due to their
location in the tidal streams in which they form (e.g. Mirabel et al.
1992; Duc et al. 2000; Weilbacher et al. 2003; Duc et al. 2011,
2014). However, the same streams that identify these objects as
TDGs also indicate tidal distortion of their velocity fields, so that
dynamical masses cannot be reliably measured, nor can the presence
or absence of DM be determined (Casas et al. 2012). For example,
dwarf galaxies in obviously interacting systems such as the Perseus
Cluster have comparable M/L ratios (∼120 M⊙/L⊙) to the CDM
dwarf satellites of the Milky Way (Penny et al. 2009). The exception
to this problem is where tidal streams are old and faded, as in
Duc et al. (2014), and the TDG has had time to reach dynamical
equilibrium.

The aim of this paper is first to detect TDGs based on their
elevated metallicity and falling rotation curve alone, without the
presence of tidal streams that confuse kinematic measurements. To
that end, here we present rotation curves and metallicities for a sam-
ple of star-forming dwarfs in gas-rich galaxy groups, many of which
do not have obvious evidence of tidal streams. Section 2 outlines
our sample selection, observations and data processing. In Section
3, we present our results, including rotation curve modelling, mass-
to-light ratio, and one rapidly falling rotation curve. Finding that
the rotation curves of many galaxies in the sample are distorted
even without the presence of obvious tidal streams, in Section 4 we
discuss the survival and detectability of TDGs in the group environ-
ment; this is the second main aim of the paper. Section 5 concludes
the paper. The appendices contain notes on and rotation curves for
individual galaxies in the sample.

2 SAMPLE SELECTION, OBSERVATIONS AND
DATA PROCESSING

Our sample consists of dwarf galaxies within the star-forming, gas-
rich groups known as Choirs (Sweet et al. 2013). These 15 groups of
four or more Hα emission line galaxies were detected in the Survey
for Ionization in Neutral Gas Galaxies (SINGG Meurer et al. 2006),
a follow-up Hα imaging survey to the HI Parkes All Sky Survey
(HIPASS Barnes et al. 2001).

In Sweet et al. (2014), we presented ANU 2.3-m WiFeS (Dopita
et al. 2007) integral field spectroscopy for 53 galaxies in eight of
these Choir groups. We measured spatially integrated metallicities
for that sample in order to identify a sample of TDG candidates
based on elevated metallicity for their R-band magnitude. To con-
firm whether or not they are true TDGs, we set out to measure
their rotation curves; a falling rotation curve would demonstrate the
absence of a dark matter (DM) halo as expected for such galaxies.
However, with the small telescope aperture we do not enjoy suffi-
cient signal-to-noise to allow resolved kinematic analyses of the
faint dwarfs in the sample.

We therefore obtained Keck DEIMOS (Faber et al. 2003) spec-
troscopy for four Choir groups on 2013 February 11; two groups
(J1051−17 and J1403−06) from our WiFeS sample and two new
groups (J0443−05 and J1059−09), being sources with observable
right ascensions during the allocated observing date. We used the
1200L grating with central wavelength 5950 Å and the GG400
order-blocking filter. Each group was observed for six 1200-s expo-
sures. Mask and slit placements are shown in Appendix C. We chose
the mask position angle (PA) to facilitate observing as many of our
Choir member galaxies as possible. The remaining spare mask area
was used to allocate slits to other sources suggestive of some net Hα
emission in the SINGG imaging but not already identified, with the
intention of detecting new member group galaxies. This selection
expanded our sample to ∼100 objects per mask.

Data processing was conducted using the DEIMOS DEEP2 data
reduction pipeline.1 This pipeline is optimized for compact sources
observed with a central wavelength of around 7700 Å, so we em-
ployed Evan Kirby’s modification2 to enable processing of our bluer
wavelengths. We also modified the sky subtraction routines to give
more flexibility for extended sources, as most of our galaxies are
sufficiently extended to fill their slits. In these cases, we selected
a section of another slit that contains some sky to perform a non-
local sky subtraction. While there is some residual sky emission
due to variations in the observed sky spectrum caused by slit angle
and width differences and path through the optics and detector, the
residual sky emission does not overlap with the Hα for the redshifts
of our groups, so the result is adequate for velocity measurements.

We used our own software to extract a portion of the spectrum at
the expected Hα wavelength for each row of binned pixels, and fit
a single Gaussian profile to the peak to measure redshift. There is
no evidence for multiple components at the resolution of our data.
The peak location error from the χ2-minimization fit is used to de-
rive the 1σ observed velocity errors quoted herein. The Hα width
and flux and continuum flux were also measured for each bin. In
order to measure the true profile width, the spectrum cutout was
deconvolved with a line spread function (LSF) measured from a
nearby bright sky line. Importantly, we noticed that the LSF varied
significantly with the tilt and location of the slit on the mask, so we
chose a sky line in each slit for the LSF measurement. Heliocentric
velocity corrections were calculated using the IRAF package RVCOR-
RECT. Our measurements confirm that six of the potential member
galaxies in two groups lie at the group redshift; these are included
in Table 1. We used the methods outlined in Meurer et al. (2006)
to measure these new galaxies’ extinction-corrected R-band magni-
tudes, surface brightness profiles and effective radii from the SINGG
imaging.

We observed one spectrophotometric standard star for each mask
and performed flux calibration in the standard manner.

We measured the integrated metallicity of each galaxy by col-
lapsing spectra in the spatial direction and fitting a Gaussian profile
to these integrated spectra to measure strong emission line fluxes.
The wavelength range of DEIMOS 1200L grating with our central
wavelength covers most of the necessary strong emission lines for
using the Dopita et al. (2013) [N ii]/[S ii] versus [O iii]/[S ii] di-
agnostic. This is the same calibration as used in Sweet et al. (2014);
we give a discussion of our reasons for choosing it in that paper.
Briefly, this diagnostic gives consistent results with recombination
and electron temperature methods; the necessary lines are available
in most of our sample; and is not degenerate, clearly separating ion-
ization parameter and metallicity: the [N ii]/[S ii] ratio is sensitive
to metallicity, while the [O iii]/[S ii] ratio tells the dependence on
ionization parameter. The metallicities derived from the DEIMOS
data are not corrected for reddening in most cases, because most do
not have measurable H β, with the line either lost in the noise of
the blue end, or fallen off of the chip. In any case, the diagnostic is
not very dependent on reddening: because the [N ii] and [S ii] lines
are nearby in wavelength, the [N ii]/[S ii] ratio will not vary much with
reddening.

1 http://www2.keck.hawaii.edu/inst/deimos/pipeline.html
2 http://www2.keck.hawaii.edu/inst/deimos/calib_blue.html
| HIPASS+ | RA (h m) | Dec. (d m) |reff (°) | a/b | PA (°) |corr. | $M_R$ (mag) | $r_0$ (kpc) | $l_0$ (L⊙kpc⁻¹) | $V_{rot}$ (km s⁻¹) |
|--------|--------|---------|--------|------|--------|-------|------------|------------|----------------|------------------|
| J0443−05:S3 | 04 44 11.67 | −05 14 38.31 | 04.79 ± 0.19 | 1.86 | 19 | 0.883 | −19.93 ± 0.19 | 1.809 | 2.3E+8 | 4591 |
| J0443−05:S4 | 04 44 05.54 | −05 25 46.50 | 04.95 ± 0.12 | 1.6 | 120 | 0.537 | −19.07 ± 0.12 | 1.048 | 5.9E-8 | 4774 |
| J1051−17:S3 | 10 51 35.94 | −16 59 16.80 | 06.61 ± 0.05 | 1.02 | 74 | 0.048 | −18.14 ± 0.05 | 2.232 | 4.7E-7 | 5969 |
| J1051−17:S4 | 10 51 26.01 | −17 05 03.61 | 03.48 ± 0.09 | 1.4 | 164 | 0.661 | −16.34 ± 0.09 | 0.837 | 7.5E-7 | 5465 |
| J1051−17:S5 | 10 51 50.91 | −16 58 31.64 | 03.58 ± 0.06 | 1.75 | 29 | 0.865 | −17.20 ± 0.06 | 0.842 | 9.1E-8 | 5465 |
| J1051−17:S6 | 10 51 42.78 | −17 06 34.59 | 02.11 ± 0.04 | 1.29 | 40 | 0.422 | −16.95 ± 0.04 | 0.492 | 3.0E-8 | 5648 |
| J1051−17:S7 | 10 51 33.36 | −17 08 36.63 | 04.18 ± 0.12 | 1.53 | 49 | 0.802 | −16.94 ± 0.12 | 0.799 | 1.2E-8 | 5374 |
| J1051−17:S8 | 10 51 25.92 | −17 08 16.44 | 04.47 ± 0.10 | 3.07 | 63 | 0.927 | −18.17 ± 0.04 | 0.804 | 7.5E-8 | 5294 |
| J1051−17:g04 | 10 51 39.67 | −17 03 34.16 | 02.97 ± 0.14 | 1.06 | 43 | 0.21 | −18.10 ± 0.05 | 1.45 | 5.0E-7 | 5535 |
| J1051−17:g07 | 10 51 43.698 | −17 01 42.99 | 03.34 ± 0.09 | 1.12 | 42 | 0.3 | −16.21 ± 0.08 | 0.95 | 4.0E-7 | 6166 |
| J1051−17:g11 | 10 51 40.051 | −16 57 30.94 | 01.95 ± 0.13 | 1 | 47 | 0.027 | −16.37 ± 0.11 | 0.28 | 1.3E-9 | 5371 |
| J1051−17:g13 | 10 51 41.602 | −17 05 20.16 | 01.52 ± 0.16 | 1.05 | 42 | 0.21 | −14.94 ± 0.21 | 0.685 | 8.0E-6 | 5577 |
| J1051−17:g15 | 10 51 33.286 | −17 09 19.17 | 05.26 ± 0.85 | 1.05 | 42 | 0.21 | −15.18 ± 0.81 | 2.63 | 4.0E-6 | 5225 |
| J1059−09:S2 | 10 59 06.77 | −09 45 04.38 | 11.72 ± 0.24 | 1.36 | 131 | 0.056 | −20.19 ± 0.24 | 5.271 | 4.7E-7 | 8013 |
| J1059−09:S5 | 10 59 30.98 | −09 44 25.26 | 09.11 ± 0.13 | 2.84 | 75 | 0.968 | −19.94 ± 0.13 | 2.973 | 2.4E-8 | 7926 |
| J1059−09:S7 | 10 59 21.31 | −09 47 50.49 | 02.50 ± 0.15 | 1.59 | 115 | 0.167 | −19.13 ± 0.15 | 0.761 | 1.2E-9 | 7862 |
| J1059−09:S9 | 10 59 01.73 | −09 52 46.76 | 03.47 ± 0.40 | 1.81 | 155 | 0.702 | −16.98 ± 0.40 | 1.028 | 9.4E-7 | 8260 |
| J1059−09:S10 | 10 59 02.64 | −09 53 28.60 | 01.99 ± 0.08 | 1.39 | 45 | 0.604 | −16.63 ± 0.08 | 0.63 | 2.0E-8 | 8475 |
| J1403−06:S3 | 14 03 13.48 | −06 06 24.17 | 04.18 ± 0.85 | 1.03 | 14 | 0.158 | −15.38 ± 0.85 | 0.448 | 7.5E-7 | 2753 |
| J1403−06:S4 | 14 03 34.62 | −06 07 59.27 | 05.96 ± 0.86 | 1.43 | 123 | 0.731 | −14.51 ± 0.86 | 0.961 | 1.4E-7 | 2671 |
| J1403−06:g1 | 14 03 22.475 | −06 00 44.24 | 03.57 ± 0.36 | 2.04 | 46 | 0.76 | −13.58 ± 0.39 | 2.51 | 6.3E-6 | 2692 |

(12−16) observed flux for various emission lines in units of 10⁻²² erg s⁻¹ cm⁻²; [O III] $\lambda$5006.9, [N II] $\lambda$6583.4, [S II] $\lambda$6717.0+6731.3; (17) estimated ionization parameter based on Dopita et al. (2013) interpolation if [O III] available, or on $M_R$−log(q) relation of other galaxies in this sample otherwise; (18) 12+log(O/H) using Dopita et al. (2013) calibration; (19) membership of Sample A (based on quality of rotation curve) is indicated here by the letter ‘A’; (20) R-band mass-to-light ratio; (21) modelled rotational velocity at $r_{200}$. (22) tidal radius.
For the galaxies with all three strong emission lines available, we use the methods described in Sweet et al. (2014) to interpolate for metallicity and ionization parameter log(q). For the galaxies with only [N ii] and [S ii] available, we roughly estimated the ionization parameter log(q) based on a polynomial fit to log(q) as a function of R-band absolute magnitude $M_R$ of the DEIMOS galaxies for which all three strong lines are available; log(q) = 10.836 + 0.3593$M_R$ + 8.361×$10^{-3}$×$M_R^2$. We then used [N ii]/[S ii] and log(q) to estimate 12 + log(O/H) by inspection of the same diagnostic. These measurements are therefore less reliable and have a nominal 0.5 dex error bar to show this. While the [N ii]/[S ii] ratio alone has a similar scatter to the [N ii]/Hα calibration (e.g. Marino et al. 2013), the method just described has the added benefit of providing log(q), which gives a better constraint on the metallicity. The metallicity measurements are catalogued in Table 1.

3 RESULTS AND ANALYSIS

Our first step towards identifying TDGs aside from their location in a tidal stream is to select candidates based on their elevated metallicity; the second is to confirm the absence of DM by measuring a falling rotation curve. In this section, we employ that method, first presenting our sample of dwarf galaxies on the luminosity–metallicity relation, and then modelling their rotation curves. We then measure mass-to-light ratios for those galaxies where this can be reliably obtained. The section finishes with a discussion of one galaxy with an apparently strongly falling rotation curve.

3.1 Luminosity–metallicity relation

In Fig. 1, we plot the luminosity–metallicity relation for our full sample of WiFeS (Sweet et al. 2014) and DEIMOS (this work) measurements. In general, the galaxies with DEIMOS measurements are consistent with the portion of our sample for which we have WiFeS measurements, and with the SDSS relation defined in Sweet et al. (2014). In that paper, we identified a metallicity floor for low-luminosity galaxies in SDSS. There is a suggestion of the metallicity floor being continued to fainter magnitudes by the new measurements.

We select TDG candidates in the DEIMOS data based on our definition from Sweet et al. (2014) (12 + log(O/H) > 8.6 and more than 3σ above SDSS); these are J1051−17:011 and J1403−06:01. However, J1403−06:01 lies in the halo of its host spiral, and is probably experiencing strong tidal interactions, so is not detectable as a TDG based on its velocity profile (see Section 4).

Six of the galaxies in our sample have both WiFeS and DEIMOS metallicity measurements. In the J1403−06 group these metallicities agree to within quoted errors, even without [O iii] for the DEIMOS measurements. However, the J1051−17 group members where we can compare the data generally do not have consistent metallicities between DEIMOS and WiFeS, separated by up to 2σ. This is partly due to the missing [O iii] line for some of the DEIMOS measurements, but more generally because bright sky lines fall on the [S ii] lines at the distance of this group. There is some unavoidable sky residual for both instruments due to the non-local sky subtraction employed. The sky residuals therefore contribute to the [S ii] flux measurements and skew the metallicities for this group. We expect that the DEIMOS sky subtraction discussed above may be worse than for the WiFeS observations, where we used a nod-and-shuffle technique which minimized systematics related to optics and detector position.

![Figure 1. Luminosity–metallicity relation for the full sample of galaxies. Blue stars are existing WiFeS measurements from Sweet et al. (2014). Red stars are DEIMOS measurements. Green bars connect WiFeS and DEIMOS metallicities for five of the six galaxies that have measurements from both instruments; both measurements for J1403−06:S3 are equal. Grey points and contours depict SDSS star-forming galaxies, while the red, dashed line indicates our strong TDG candidate diagnostic. Galaxies above this line are more than 3σ above the typical metallicity for their luminosity and hence candidate TDGs.](http://mnras.oxfordjournals.org/)}
We corrected for inclination using the optical axial ratio $b/a$ from SINGG photometry, where $b$ is the semi-minor axis and $a$ is the semi-major axis, and the angle of inclination $i$ is given by $\cos(i) = \sqrt{(b/a)^2 - 0.2^2}/(1 - 0.2^2)$, the factor of 0.2 is a correction for disc thickness (Tully & Fisher 1977) and $3^\circ$ is an empirical correction for the difference in the flattening of stellar versus H I discs (Aaronson, Mould & Huchra 1980). We also corrected for angle of misalignment $\phi$ between slit PA and SINGG optical major axis PA. The misalignment is a function of the chosen slit mask PA and the constraints of the instrument; the slit PA must be $5^\circ < |PA| < 30^\circ$ with respect to the mask,limiting the choice of PA. The model rotation curve obtained from fitting the optical data is divided by the total correction of $\sin(i)\cos(\phi)$.

We do not have sufficient information to model the asymmetric drift. While we have measured the H\,$\alpha$ velocity dispersion at each point in our spectra, this emission is strongly affected by H\,$\alpha$ regions. It is not clear that these are in virial equilibrium, since their dynamics are thought to be dominated by short-lived ($\lesssim 10$ Myr) expansion from ionization, stellar winds and supernovae (Shopbell & Bland-Hawthorn 1998; Clarke & Oey 2002). The nature of the diffuse ionized gas H\,$\alpha$ between H\,$\alpha$ regions is also unclear, and in many cases is a signature of outflows such as galactic winds (Oey et al. 2007; Rodríguez-González et al. 2008). We also do not have sufficient information about the neutral and molecular ISM (which is being ionized to become H\,$\alpha$) to determine its contribution: our H\,$\alpha$ data has insufficient resolution, and we have no molecular observations. We can estimate the order of magnitude of the asymmetric drift as follows (noting that this estimate is an upper limit, since the dispersion in the H\,$\alpha$ emission is overestimated for the reasons just mentioned). The asymmetric drift correction term $\sigma_{\beta}$ as a function of radius $r$ is given by $\sigma_{\beta}^r = -r\sigma^2[\partial \ln(\Sigma_g)/\partial r + 2\partial \ln(\sigma)/\partial r - \partial \ln(h_s)/\partial r]$, where $\sigma$ is the Gaussian sigma of the 1D H\,$\alpha$ velocity profile measured as described in the previous section, $h_s$ is the vertical scaleheight of the disc and $\Sigma_g$ is the gas surface density. For most of the galaxies in the sample there is no obvious dependence of $\sigma$ on the radius, so we adopt a single median value for each galaxy, with a sample mean of 20 km s$^{-1}$. We also assume that $h_s$ is constant with radius, so the correction term becomes simply $\sigma_{\beta}^r = -r\sigma^2[\partial \ln(\Sigma_g)/\partial r]$. Making a further assumption that the ionized gas distribution is similar to the neutral gas and star distributions allows fitting an exponential profile to the natural log-scaled continuum flux as a function of $r$. The model rotation curve obtained from fitting the optical data is divided by the total correction of $\sin(i)\cos(\phi)$.
Doing so results in a mean asymmetric drift correction of around 6 km s$^{-1}$ at maximum velocity. As this is a simplified estimation only, we do not include this correction in our further analysis.

### 3.3 Rotation curve quality

Reliable mass-to-light ratios are dependent on good-quality observations. Unfortunately, not many of the rotation curves in this sample are simple to analyse: several are disturbed, having asymmetric velocity profiles, and others have multiple SF regions or possible counter-rotating cores. In our case, we restrict our M/L analysis to the galaxies that meet the following criteria:

(i) $\sin(i)\cos(\phi) > 0.4$, so there is neither a large correction for galaxy inclination nor misalignment between the slit and galaxy PA; and,

(ii) sufficiently large and bright so that the photometry is reliable (this cutoff is effectively between galaxies in the original SINGG sample and fainter galaxies identified in this work); and,

(iii) not strongly disturbed in appearance (e.g. Fig. B11).

The resulting sample, which we label Sample A, consists of 10 dwarf galaxies, out of 22 for which we have DEIMOS measurements. The galaxies within Sample A are indicated in Table 1.

The fraction of our sample that meets criterion (i) is 60 per cent [all of the galaxies in Sample A, plus three that fail criteria (ii) and (iii)]. We can calculate the expected fraction that meets the first criterion as follows. The PA misalignment is given by $\phi = PA - 30^\circ$, where the galaxy PA with respect to the mask is $30^\circ \leq PA \leq 90^\circ$, and $\phi = 0^\circ$ for $0^\circ \leq PA < 30^\circ$. For a randomly oriented galaxy, a PA of $45^\circ$ then gives a median $\phi = 15^\circ$. Half of a sample of such galaxies should therefore have $\phi \leq 15^\circ$. Solving $\sin(i)\cos(15^\circ) > 0.4$ for $i$ gives a minimum inclination of $23^\circ$, below which the amplitude in the rotation curve rapidly becomes too low to measure. For a randomly selected sample, the frequency of any given cos(inclination) should be constant, so up to $\sim \cos(23^\circ) = 92$ per cent of galaxies are more edge-on than this. The resulting expected fraction of galaxies that meets our first criterion is therefore $0.5 \times 0.92 = 46$ per cent; considerably lower than the 60 per cent in our sample. The PA calculations rely on our assumption of disc-like systems. However, the irregular galaxies may be better modelled as triaxial systems, which are more prolates. This means that there is a lower chance of observing these to be circular and measuring low, face-on inclinations in the disc-like model (van den Bergh 1988), so much of the difference between the expected and observed fraction of edge-on galaxies is likely attributable to triaxiality of the irregular galaxies. In addition to this, we also expect that there are group effects causing a non-random orientation in PAs in our sample. In particular, there is a hint of a stream of dwarf galaxies in J1051−17 (see Fig. C2), which is to be discussed in a forthcoming paper (Kilborn et al., 2015, in preparation).

### 3.4 M/L ratios

We test for the presence of DM by calculating M/L ratios through fitting model curves to observed rotational velocities as described above. A high M/L ratio implies the presence of DM and a normal hierarchical formation mechanism. In general, the M/L ratios in Sample A are low, but not dramatically so, at a mean M/L ratio of 0.73 M$_{\odot}$/L$_{\odot}$ and standard error on the mean of $\pm 0.39$ M$_{\odot}$/L$_{\odot}$. Low M/L ratios in general simply confirm that these are young galaxies forming stars. Some of our wider sample does not have sufficient signal at radii $> r_{\text{turn}}$, so that our modelling calculates lower limits on masses and mass-to-light ratios. However, this does not significantly affect Sample A, which all have reliable measurements within $r_{\text{turn}}$ and are well modelled.

We plot M/L ratios as a function of the luminosity–metallicity relation using Sample A in Fig. 3. While sparse, the data suggest a trend towards higher mass-to-light ratios with higher luminosity. This is consistent with the view that the luminosity–metallicity relation arises from the deeper potential well of larger galaxies, which makes them more able to retain metal-rich supernovae ejecta (Gibson & Matteucci 1997; Kauffmann et al. 2003).

Unfortunately, neither of the strong TDG candidates identified above is part of Sample A, so we cannot include either of them in this analysis. In essence this is because neither has a well-behaved mass-follows-luminosity rotation curve: J1051−17 has no detectable H$\alpha$ on the southern semi-major axis, and a large correction for inclination; J1403−06 has a disturbed rotation curve.

An improved strategy for identifying TDGs in this manner is (1) measure metallicities with low-resolution spectra of as many galaxies as possible in a field, preferring those with easiest (edge-on) inclinations; and (2) measure rotational velocity with medium-resolution spectra of a subset of these, either optimizing slit orientation for the high-metallicity candidates, or using an integral field spectrograph. In this way, the effects of large inclination/PA corrections can be minimized. However, this strategy does not take into account tidally disturbed or stripped matter at the outskirts of target galaxies, leading us to consider that problem in Section 4.

### 3.5 The apparently strongly falling rotation curve of J0443−05:54

As discussed in the previous sections, no galaxy in our sample that is a strong TDG candidate, based on elevated metallicity, exhibits a falling rotation curve. Relaxing the metallicity criterion somewhat, our next best candidate for a TDG based on metallicity and rotation curve is HIPASS J0443−05:54 shown in Fig. 2. In terms of metallicity, this galaxy is $12 + \log(O/H) = 8.86$ and $R$-band magnitude $M_R = -19.07$, placing it within the metallicity–luminosity relation defined by the SDSS control sample. However, it is near a giant spiral S2 which has a metallicity just 0.32 dex higher at $12 + \log(O/H) = 9.18$.
and $M_B = -22.57$. We note that these differences in magnitude and metallicity are similar to those measured in the M31–M32 system ($\Delta\text{mag} = 4.43$; $\Delta$metallicity = 0.22 dex; Richer, McCall & Stasińska 1998), for which a tidal encounter has been proposed (e.g. Faber 1973; Bekki et al. 2001; Choi, Guhathakurta & Johnston 2002).

The measured rotation curve is falling rapidly beyond the turnover radius $r_{\text{turn}}$, indicating that DM is not required to explain its observed velocity (though it is not disallowed). In fact, the rotation curve shows a significant down-turn below the mass-follows-light profile shown in blue, even reaching zero at the outskirts of the galaxy. This galaxy is near our nominal detection limit of $r_{\text{fidal}} = 2r_{\text{turn}}$, indicating that there could be some tidal warping of the rotation curve. However, the symmetry of this system indicates it is not subject to extreme tidal forces, so we do not believe that tides are causing the severe down-turn. The rapidly falling rotation curve is not consistent with the predictions for a TDG, and the lack of evidence for tides corroborates this. The error bars (derived from the peak location error in the $\chi^2$-minimization fit to the H$\alpha$ line) indicate that low S/N is not responsible for the unusual shape of this rotation curve. Nor can the downturn be attributed to instrumental signatures or residual sky lines; the same shape is observed for other emission lines in this system, which fall in other locations on the detector.

Clearly, a simplified disc model is not adequate to describe this galaxy. We propose two scenarios that may explain the stronger detector. signatures or residual sky lines; the same shape is observed for other emission lines in this system, which fall in other locations on the detector.

First, we consider a polar ring galaxy, where the central, rising observed velocity profile belongs to a tilted inner bar, and the falling profile to a face-on outer disc with no measurable rotation. The observed morphology hints at a central bar, though more detailed imaging is required to confirm this. This polar ring structure is not unusual in a dwarf (cf. De Rijcke, Buyce & Koleva 2013), but could conceivably arise as a tilt to the galaxy’s existing disc, triggered by an interaction with the neighbouring giant galaxy S2, if not the typical (for giant polar ring galaxies) method of accreting material from the nearby galaxy (Athanassoula & Bosma 1985). The size of the bar relative to the disc in this scenario is reminiscent of the morphological (cf. dynamical) bar of the LMC, as is the dwarf-giant separation ($\sim 50$ kpc in both cases). van der Marel & Kallivayalil (2014) recently measured the LMC (stellar) rotation curve, but due to the high degree of scatter in the stellar velocities there is no clear trend in the outskirts of the galaxy with which to compare J0443−05:S4.

Secondly, the more critical issue is that the strong tidal fields that form a TDG, together with the low interior mass density expected for a DM-free TDG torn from the low-density outskirts of galaxies, lead to the tidal stripping of the outer baryonic matter of the TDG. With all other things equal, a normal galaxy with the same stellar mass as a TDG should be better able to survive tidal stretching because of its DM which increases its cohesion. Tidal stripping makes the measurement impossible when $2r_{\text{fidal}} > r_{\text{del}}$, where $r_{\text{fidal}} = 0.4d(m/M)^{1/3}$ is the tidal radius of the dwarf galaxy (for a fluid, triaxial satellite, as in Shi 1982); $d$ = distance of closest approach, $m$ = mass of dwarf galaxy, $M$ = mass of giant host galaxy. It is worth noting that the velocity field will be disturbed even before the proximity criterion for stripping is reached, for instance Bekki & Couch (2011) showed that the rotation curve of an MW-type galaxy changes over time with tidal heating. As discussed in Renaud et al. (2009), tidal fields are in fact compressive as well as destructive; while the destructive stretching acts to pull galaxies apart, it is the compression mechanism that is responsible for the formation of TDGs. Aguilar & White (1986) also pointed out that while strong tidal encounters decrease the effective radius of a galaxy, weak encounters puff up the galaxy instead, e.g. by galaxy harassment (Moore et al. 1996). This disturbance is also problematic for a sound measurement of a rotation curve. However, we do not attempt to quantify this here for the sake of simplicity in this analysis.

We calculate $r_{\text{fidal}}$ for each galaxy in our sample, assuming $d = \sqrt{2}d_{\text{proj}}$, where $d_{\text{proj}} = \text{projected distance to the nearest large galaxy}$, and the factor of $\sqrt{2}$ is based on a 45° projection angle. This assumes that the deprojected distance is the distance of closest approach. It is
that have been identified based on their location within tidal streams, falling rotation curve, so none is a TDG.

there must also be sufficiently bright Hα galaxies lies above this line then those baryons remain bound, but where the falling-velocity baryons do not remain bound. If a dwarf and giant galaxy, respectively, so that \( r_\alpha \) turn detection limit before the galaxy can be detected as a TDG.

In Fig. 4, we plot \( r_{\text{tidal}} \) versus \( r_e \); the dashed line indicates the required radius of \( 2r_{\text{turn}} \). Four of the 22 galaxies in our sample fall below this line, indicating that these could not be dynamically confirmed. A further five to six galaxies are borderline. Others in this sample could also be unidentifiable, given that the tidal radius is likely overestimated. Clearly, a large \( r_{\text{tidal}} \) is required for a galaxy to be dynamically confirmed to be a TDG; that is, the dwarf must be far from the nearest giant. However, the further away from the giant, the less likely the dwarf is to be formed in a tidal manner (c.f. J0443−05:S3, which has the largest \( r_{\text{tidal}} \) in the sample, and a flat (DM-rich) rotation curve, so is not a TDG). Further to this, we reiterate that the \( 2r_{\text{turn}} \) detection limit only indicates where the falling-velocity baryons do not remain bound. If a dwarf galaxy lies above this line then those baryons remain bound, but there must also be sufficiently bright Hα to meet the detectability radius \( r_{\text{det}} \) criterion before the galaxy can be detected as a TDG. Even with these DEIMOS observations only 13 (per cent) galaxies have \( r_{\text{det}} \geq 2r_{\text{turn}} \) (shown as yellow pentagons in Fig. 4): J0443−05:S3, J1051−17:S5, J1059−09:S7. None of these has a falling rotation curve, so none is a TDG.

This effect is problematic for TDG candidates in the literature that have been identified based on their location within tidal streams, because the strong tides distort the rotation curves and dynamical M/L ratios. This is clear in the work by Mendes de Oliveira et al. (2001), who used velocity gradients to ascertain whether or not star-forming regions within tidal tails in Stephan’s Quintet would remain bound, forming TDGs. None of the rotation curves shows a fall-off in velocity, and all are severely disturbed by the tidal field. The M/L ratios measured are inflated (5–73 M⊙/L⊙), requiring DM in opposition to expectations for TDGs. It may be argued that one can do better with Hα measurements, probing to larger radii than Hα. Declining rotation curves are seen in some galaxies observed in Hα including DDO 154 (Carignan & Burton 1998; Hoffman, Salpeter & Carle 2001; however cf. de Blok et al. 2008) and NGC 300 (Westmeier, Braun & Koribalski 2011). In the case of DDO154, this measurement was possible because the galaxy is isolated and hence is not tidally truncated. However, this mass includes a substantial DM component and therefore rules out a tidal origin for this galaxy.

Measurements of falling rotation curves remain difficult, except for a few selected cases.

5 CONCLUSIONS

In this paper, we presented DEIMOS observations of a sample of 22 star-forming dwarf galaxies in gas-rich groups. After prioritizing our known group members in the slit mask design, we placed spare slits on as many sources as possible, with preference to galaxy-like photometry. In doing so, we identified six additional small galaxies across two of the groups.

We measured the metallicity of those galaxies within our sample that have the necessary strong emission lines and found two new very strong TDG candidates (J1051−17:g11 and J1140−06:g1).

We constructed rotation curves for the dwarf galaxies in our sample and modelled them with a mass-follows-light fit to the central regions of each galaxy. All but one of the galaxies show signs of rotation with a mean of 39.3 kms⁻¹ at \( r_{\text{turn}} \), but most of the velocity profiles are disturbed so that a mass-follows-light profile does not fit the data, and neither does a mass-follows-light plus a DM component. The generally disturbed nature of the velocity profiles indicate that these galaxies are tidally perturbed.

M/L ratios in our sample are low (0.73 ± 0.39 M⊙/L⊙), indicating that the stellar populations in these galaxies are young, consistent with their high rates of star formation. There is some suggestion of a trend of M/L ratio with luminosity in our sample, with fainter galaxies having lower mass-to-light ratios.

One galaxy in our sample, J0443−05:S4, has an apparently strongly falling rotation curve, reaching zero velocity at the outskirts of the galaxy. We propose that we may be observing either (1) a polar ring galaxy, with a tilted inner structure and face-on outer skirts of the galaxy. We suggest that we may be observing either (1) a polar ring galaxy, with a tilted inner structure and face-on outer disc; (2) a kinematic twist due to a warped disc, with the line of nodes falling within the edges of the slit.

Even with very high sensitivity DEIMOS data, it remains difficult to convincingly measure the falling rotation curve of a TDG, due to both physical and observational effects. Observationally, the limitations of slit–galaxy PA alignment severely constrain our ability to reliably measure kinematics of all galaxies in a group. To overcome these observational effects, integral field unit spectroscopy should be employed. For DEIMOS with a constraint of ±30°, we have reliable measurements for 60 per cent of our sample. This is considerably greater than the predicted 37.5 per cent, suggesting that the PAs of the galaxies are aligned, perhaps due to group effects.

Physically, many of the rotation curves in our sample are disturbed due to recent interaction, or are not smooth due to having multiple star-forming regions. In addition to this, the outskirts of many of the dwarfs may be tidally stripped by interactions with
neighbouring galaxies. As much as half of our sample could be affected by this. Even in the absence of tidal stripping, H\alpha light rapidly becomes progressively fainter beyond the turnover radius. Only 14 per cent of our sample has detectable H\alpha light at sufficient radii to measure any fall in rotation curve; none of these has a falling rotation curve, so none is a TDG. It seems that falling rotation curves expected of TDGs can be detected only rarely, if at all.

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APPENDIX A: SAMPLE A

A1 Notes on individual galaxies

J0443−05:S3 (Fig. A1). This galaxy is the most ‘normal’ in our sample, with a small stellar bulge (cyan) surrounded by a star-forming disc (red), and a flat rotation curve, consistent with a DM halo. Its tidal radius is much larger than its effective radius, borne out by the large radius to which we measure a typical rotation curve. It also has the highest M/L ratio in our sample at 4.15 $M_\odot/L_\odot$.

J0443−05:S4 (Fig. 2). This galaxy has a stronger than Keplerian fall-off in its rotation curve. It is depicted in Fig. 2 and is discussed in detail in Section 3.5.

J1051−17:S4 (Fig. A2). This galaxy has three separate SF regions, with velocity rising linearly with position along slit, consistent with solid body rotation. The observed rotation rises above the
model predictions, suggestive of the presence of DM. It has a low M/L ratio (0.58 M⊙/L⊙), consistent with most of the dwarfs in our sample.

J1051−17:S5 (Fig. A3). There appear to be two SF regions in this galaxy. The velocity profile of this galaxy is not well fitted by the canonical mass-follows-light rotation curve. However, this galaxy is not likely suffering from tidal effects due to its position on the \( r_{\text{tidal}} - r_e \) plot.

J1051−17:S6 (Fig. A4). This galaxy has a velocity similar to the disc of the nearby giant S1. The observed velocity profile of S6 is distorted beyond \( r_{\text{num}} \) by its proximity to S1.

J1051−17:S7 (Fig. A5). S7 is the brighter feature to the W of the slit (that is, the bottom of this figure). Also measured in this slit is an H\alpha region in the plane of the disc of S1 (‘S7a’), towards the top of this figure. The velocity profile shown here is that of S7 only.
It is disrupted, consistent with this galaxy having recently passed through the disc of S1 and possibly inducing star formation in S7a. Its velocity is clearly offset from the velocity of the neighbouring disc of S1, but the shape of the spiral arm of S1 passing near S7 is distorted and the Hα emission is enhanced, strongly suggesting a recent interaction.

J1051−17:S7 (Fig. A5). The velocity profile of this galaxy is consistent with a mass-follows-light profile with a kinematically decoupled core. The faint Hα emission and bright continuum at the centre makes the velocity profile difficult to measure beyond the region shown here, especially at the NE end of the slit. The apparent Hα absorption in the central panel is in fact an adjacent, poorly subtracted sky line.

J1051−17:S8 (Fig. A6). The velocity profile of this galaxy is consistent with a mass-follows-light profile with a kinematically decoupled core. The faint Hα emission and bright continuum at the centre makes the velocity profile difficult to measure beyond the region shown here, especially at the NE end of the slit. The apparent Hα absorption in the central panel is in fact an adjacent, poorly subtracted sky line.

J1059−09:S5 (Fig. A7). For this slit, Hα and [N II] lines fall on the edge of the CCD, so we opt for the [O III] λ 5007 line.
in our kinematical analysis in order to avoid possible edge of frame effects. Similar observations with a slit better placed with respect to the mask centre would result in H\alpha kinematics extending \( \sim 1 \) kpc beyond what we show for [O III] 5007. The observed velocity rises above the model curves, suggestive of the presence of DM.

J1059−09:S8 (Fig. A8). Mass follows light for this small galaxy. It has a metallicity 2.5\( \sigma \) above the SDSS mean for its luminosity, so is close to our TDG selection limit. Moreover, it is near in projection to the very high metallicity dwarf S10 and may be related to it.

J1059−09:S9 (Fig. A9). This small galaxy has very low surface brightness.
APPENDIX B: SAMPLE B

B1 Notes on individual galaxies

J1051−17:S3 (Fig. B1). This galaxy is face-on, so no meaningful velocity profile is measurable.

J1051−17:g04 (Fig. B2). The misalignment between optical and slit PAs prohibits sound measurement of this small, newly identified galaxy.

J1051−17:g07 (Fig. B3). This new, faint galaxy has strong Hα emission but very faint continuum.

J1051−17:g11 (Fig. B4). For this new galaxy there is a very large correction for inclination and orientation. There are no observed data points below the continuum centre in Fig. B4 because there is insufficient Hα light on this side of the galaxy. Its high metallicity leads us to classify this galaxy as a very strong TDG candidate.
J1051−17:g13 (Fig. B5). This galaxy’s inclination is uncertain, so it is difficult to measure its mass-to-light ratio. Its velocity profile appears to be disturbed.

J1051−17:g15 (Fig. B6). This galaxy has very low surface brightness, so is barely evident in the SINGG image. Its extent in Hα is well below the tidal truncation size and the velocity structure along the slit is erratic but has low amplitude.

J1059−09:S2 (Fig. B7). This clumpy galaxy is consistent with a mass-follows-light profile. Note that the large corrections for slit PA and galaxy inclination contribute to the large M/L ratio.

J1059−09:S7 (Fig. B8). The velocity profile of this galaxy has a very unusual shape. It is very near the interacting galaxies S1 and S3, so is likely disturbed by their tides. Moreover, the slit is close to...
aligning with the minor axis of this galaxy, so the kinematics may be indicative of a galactic wind.

J1059–09:S10 (Fig. B9). This galaxy has a very strong stellar component (as evidenced by the blue colour in Fig. B9). Its rotation curve is not well fit by a predicted mass-follows-light relation. The galaxy has a possible counter-rotating Hα absorption component, the analysis of which is beyond the scope of the paper. It has a fairly high metallicity consistent with a TDG, though not above our diagnostic cut. However, it is not near a host, so must be an old TDG if it is one. It is near another dwarf (S8) of metallicity $\sim 2.5\sigma$ above the SDSS control sample.
J1403−06:S3 (Fig. B10). This slit measures an offset H\textsc{ii} region within a very low surface brightness dwarf galaxy, so it is difficult to claim that this galaxy is rotating. It is only marginally detectable based on our $r_{\text{tidal}}$ detection limit, and indeed we do not measure rotation past $r_{\text{turn}}$.

J1403−06:S4 (Fig. B11). This very low surface brightness galaxy consists of two SF regions likely disturbed by the two giant interacting galaxies S1 and S2. It is sufficiently small to lie below the detection limit set by $r_{\text{tidal}}$.

J1403−06:g1 (Fig. B12). This appears to be a giant H\textsc{ii} region within the halo of the giant galaxy S2. It has high metallicity consistent with a TDG, but a very warped rotation curve. Due to its small size and proximity to S2, it is well below the tidal stripping detection limit.
Figure B8. J1059−09:S7. As for Fig. 2.

Figure B9. J1059−09:S10. As for Fig. 2.
Figure B10. J1403−06:S3. As for Fig. 2.

Figure B11. J1403−06:S4. As for Fig. 2.
APPENDIX C: MASK AND SLIT PLACEMENT

Figure C1. SINGG image of HIPASS J0443−05 showing locations of slits (red) for measured galaxies (green labels). The approximate location of the DEIMOS mask is given by the red polygon. The other slits are not shown for clarity.

Figure C2. SINGG image of HIPASS J1051−17 showing locations of slits (red) for measured galaxies (green labels). The approximate location of the DEIMOS mask is given by the red polygon. The other slits are not shown for clarity.
Figure C3. SINGG image of HIPASS J1059−09 showing locations of slits (red) for measured galaxies (green labels). The approximate location of the DEIMOS mask is given by the red polygon. The other slits are not shown for clarity.

Figure C4. SINGG image of HIPASS J1403−06 showing locations of slits (red) for measured galaxies (green labels). The approximate location of the DEIMOS mask is given by the red polygon. The other slits are not shown for clarity.

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