Gas dynamics in tidal dwarf galaxies: disc formation at $z=0$


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Gas dynamics in tidal dwarf galaxies: Disc formation at $z = 0^{*}, {**}, {***}, {****}$

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ABSTRACT

Tidal dwarf galaxies (TDGs) are recycled objects that form within the collisional debris of interacting and merging galaxies. They are expected to be devoid of non-baryonic dark matter, since they can only form from dissipative material ejected from the discs of the progenitor galaxies. We investigate the gas dynamics in a sample of six bona fide TDGs around three interacting and post-interacting systems: NGC 4694, NGC 5291, and NGC 7252 (“Atoms for Peace”). For NGC 4694 and NGC 5291, we analyse existing H I data from the Very Large Array (VLA), while for NGC 7252 we present new H I observations from the Jansky VLA, together with long-slit and integral-field optical spectroscopy. For all six TDGs, the H I emission can be described by rotating disc models. These H I discs, however, have undergone less than a full rotation since the time of the interaction/merger event, raising the question of whether they are in dynamical equilibrium. Assuming that these discs are in equilibrium, the inferred dynamical masses are consistent with the observed baryonic masses, implying that TDGs are devoid of dark matter. This puts constraints on putative “dark discs” (either baryonic or non-baryonic) in the progenitor galaxies. Moreover, TDGs seem to systematically deviate from the baryonic Tully–Fisher relation. These results provide a challenging test for alternative theories like MOND.

Key words. dark matter – galaxies: interactions – galaxies: dwarf – galaxies: irregular – galaxies: kinematics and dynamics – galaxies: formation

1. Introduction

During the collision of two disc galaxies, tidal forces strip material from the discs and form long tails of gas and stars (Toomre & Toomre 1972). Zwicky (1956) was the first to suggest that gas can concentrate in the tidal debris and collapse under self-gravity, leading to the formation of a new object: a tidal dwarf galaxy (TDG). Tidal debris around galaxy mergers often contains gas and stellar condensations that have masses, sizes, and star-formation rates (SFRs) comparable to those of dwarfs (e.g. Duc et al. 2000; Bournaud & Duc 2006; Recchi et al. 2007; Ploeckinger et al. 2014, 2015). For example, they should show a velocity gradient that is kinematically decoupled from the surrounding tidal debris, pointing to a local gravitational potential well. Such kinematic decoupling has actually been observed in some TDG candidates, e.g. Bournaud et al. (2007, hereafter B07) and Duc et al. (2007, hereafter D07). Since TDGs are formed out of material that is pre-enriched in the progenitor galaxies, they are found to have higher metallicities than typical dwarfs (Duc & Mirabel 1998; Weilbacher et al. 2003) and are often detected by CO observations (Braine et al. 2001; Duc et al. 2007; Boquien et al. 2010; Dabringhausen & Kroupa 2013). To be considered as bona fide TDGs, these condensations must be self-gravitating entities that can survive for several Gyr against internal or external disruption (e.g. Duc et al. 2000; Bournaud & Duc 2006; Recchi et al. 2007; Ploeckinger et al. 2014, 2015). For example, they should show a velocity gradient that is kinematically decoupled from the surrounding tidal debris, pointing to a local gravitational potential well. Such kinematic decoupling has actually been observed in some TDG candidates, e.g. Bournaud et al. (2007, hereafter B07) and Duc et al. (2007, hereafter D07). Since TDGs are formed out of material that is pre-enriched in the progenitor galaxies, they are found to have higher metallicities than typical dwarfs (Duc & Mirabel 1998; Weilbacher et al. 2003) and are often detected by CO observations (Braine et al. 2001; Duc et al. 2007; Boquien et al. 2010). The systematic deviation of young TDGs from the mass-metallicity relation has also been used to identify older TDG candidates, which are no longer embedded in collisional debris (Hunter et al. 2000; Sweet et al. 2014; Duc et al. 2014).

A key aspect of TDGs is that they are expected to be free of non-baryonic dark matter (DM; Barnes & Hernquist 1992; Elmegreen et al. 1993). This occurs because of two basic
Fig. 1. Optical images of the selected systems overlaid with FUV emission from GALEX (pink) and H I emission from the VLA (blue). TDGs are indicated in yellow. North is up; east is left. The bar to the top-right corner corresponds to \( \sim 10 \) kpc for the assumed distances (as given in Table 1). NGC 5291 (left): composite ESO-NTT \((BVR)\) and DSS image from B07. NGC 4694 (top-right): MegaCam/CFHT image obtained as part of NGVS (Ferrarese et al. 2012). NGC 7252 (bottom-right): composite ESO-MPG \((BR)\) image from Baade et al. (1999).

Dynamical principles: (i) tidal forces have different effects on the dynamically cold disc and on the dynamically hot halo, thus they effectively segregate baryons in the disc (which end up forming tails, debris, and TDGs) from DM in the halo (which is too hot to form narrow tails); and (ii) once a TDG has formed, it has a shallow potential well with a typical escape velocity of a few tens of km s\(^{-1}\), thus it cannot accrete dynamically hot DM particles with velocity dispersions of \( \sim 200 \) km s\(^{-1}\). High-resolution numerical simulations, including gas and star formation, confirm that TDGs should be nearly devoid of non-baryonic DM (Duc et al. 2004; Bournaud & Duc 2006; Wetzstein et al. 2007).

Few observational attempts have been made to measure the DM content of TDGs. Braine et al. (2001) used CO linewidths to estimate the dynamical masses of eight TDGs and found no evidence of DM. These CO observations do not resolve the gas distribution and kinematics, thus it remains unclear whether the CO linewidths can be interpreted as rotation in a local potential well. B07 presented high-resolution H I observations of the collisional ring around NGC 5291 and identified three TDGs\(^1\) that are rotating and gravitationally bound. Assuming that these TDGs and the collisional ring have the same inclination angle (as inferred from numerical models), B07 measured dynamical masses a factor of \( \sim 3 \) higher than the baryonic masses, suggesting that TDGs may contain some unconventional type of DM (either baryonic or non-baryonic). They hypothesised that the missing mass consists of very cold molecular gas, which is not traced by CO observations and is not actively forming stars, but that may constitute a large portion of baryonic DM in galaxy discs (Pfenniger et al. 1994). On the other hand, Milgrom (2007) and Gentile et al. (2007a) showed that MOdified Newtonian Dynamics (MOND) could reproduce the observed rotation velocities of these TDGs, providing an alternative explanation to the missing mass without any need of DM. As pointed out by Kroupa (2012), TDGs may help to distinguish between MOND and the standard model of cosmology, given that these two paradigms predict different internal dynamics for these recycled galaxies.

In this paper we present a systematic study of a sample of six genuine TDGs around three nearby systems: the late-stage merger NGC 7252 (“Atoms for Peace”), the collisional galaxy NGC 5291, and the disturbed lenticular NGC 4694 (see Fig. 1). Specifically, we build 3D disc models to study the HI kinematics of the TDGs and constrain their inclination angles. These techniques have been widely used and validated for typical dwarf galaxies (Swaters 1999; Swaters et al. 2009; Gentile et al. 2007b, 2010; Lelli et al. 2012a,b, 2014b). For NGC 7252, we present new H I data from the Karl G. Jansky Very Large Array (VLA) together with long-slit and integral-field optical spectroscopy from the Very Large Telescope (VLT). For NGC 5291 and NGC 4694, we re-analyse existing H I data from the VLA. In particular, we revisit the DM content estimated by B07 for the TDGs around NGC 5291.

2. Galaxy sample

Table 1 lists the basic properties of the systems in our sample and their bona fide TDGs. All six TDGs satisfy the following

\(^1\) Strictly speaking, the recycled objects around NGC 5291 are not tidal dwarf galaxies because they are not formed in tidal debris but in a collisional ring. For simplicity, we refer to them as TDGs since they are expected to share similar properties.
requirements: (i) they are "genuine" condensations of gas and young stars, which are not due to projection effects along the debris (see e.g. Bournaud et al. 2004); (ii) they have higher nebular metallicities than galaxies of similar mass, indicating that they are not pre-existing dwarf galaxies; (iii) they display a velocity gradient that appears kinematically decoupled from the tidal debris, pointing to a local potential well. For the TDGs around NGC 7252, the validity of these requirements is demonstrated in Sect. 4. For the TDGs around NGC 4694 and NGC 5291, we refer to D07 and B07, respectively. Here we provide a concise description of these systems.

2.1. The disturbed lenticular NGC 4694

NGC 4694 is a disturbed lenticular galaxy that inhabits the outskirts of the Virgo cluster. It shows asymmetric optical isophotes, dust lanes, and signs of recent star formation. A long H1 feature stretches to the west of the galaxy for ~40 kpc and contains a TDG candidate: VCC 2062 (see Fig. 1). D07 concluded that VCC 2062 is a recycled galaxy based on the following observations: (i) a high metallicity (12 + log(O/H) = 8.6); (ii) a strong CO detection; and (iii) a H1 velocity gradient that is kinematically decoupled from the debris. Recently, deep optical images have been obtained as part of the Next Generation Virgo Cluster Survey (NGVS, Ferrarese et al. 2012), revealing that NGC 4694 has a strongly perturbed halo and a prominent tidal feature to the west (Lisenfeld et al., in prep.). This confirms that NGC 4694 is the result of an old merger (>0.5 Gyr ago). The H1 kinematics of VCC 2062 is modelled in Sect. 5.1.

2.2. The collisional galaxy NGC 5291

NGC 5291 is a peculiar early-type galaxy that lies in the outskirts of the cluster Abell 3574. It is surrounded by a giant H1 ring with a diameter of ~160 kpc and H1 mass of ~5 × 10^10 M⊙ (Malphrus et al. 1997). A disturbed galaxy (the "Seashell") lies at a projected distance of ~13 kpc (see Fig. 1), but it is a fly-by object with a higher systemic velocity (~400 km s^-1, Duc & Mirabel 1998). According to the numerical model of B07, the H1 ring was formed during a head-on collision ~360 Myr ago. Notably, B07 found that the "Seashell" galaxy is not massive enough to reproduce the H1 ring and identified the elliptical IC 4329 as a more likely interloper. The H1 ring hosts several TDG candidates with nearly solar metallicities (Duc & Mirabel 1998). The three largest TDG candidates (NGC 5291N, 5291S, 5291SW) are associated with H1 velocity gradients that are kinematically decoupled from the underlying debris (B07). In Sect. 5.1 we model the H1 kinematics of these TDGs.

2.3. The advanced merger NGC 7252

NGC 7252 ("Atoms for Peace") is a prototype late-stage merger from the Toomre sequence of interacting galaxies (Toomre 1977). Numerical models have been able to reproduce its morphology and kinematics by simulating the merger of two disc galaxies falling together ~600–700 Myr ago (Hibbard & Mihos 1995; Chien & Barnes 2010). The central remnant has a single nucleus and a de Vaucouleurs luminosity profile, suggesting the morphological transformation into an elliptical galaxy (Schweizer 1982; Hibbard et al. 1994). Using VLA observations, Hibbard et al. (1994) identified two TDG candidates along the tidal tails, but the spatial and velocity resolutions of the H1 data were too low to study their internal kinematics. In this paper we show that (i) both TDG candidates are associated with a steep H1 velocity gradient that represents a kinematic discontinuity along the tail (Sect. 4.1); (ii) both galaxies have relatively high metallicities, confirming that they are not pre-existing dwarfs but are forming out of pre-enriched tidal material (Sect. 4.2); and (iii) the TDG to the north-west has a complex Hα kinematics, which is likely dominated by turbulent motions (Sect. 4.3). For both TDGs we present 3D disc models in Sect. 5.1.

3. Observations and data analysis

In this section we describe the collection, reduction, and analysis of new multiwavelength data of NGC 7252: H1 observations from the NRAO-VLA2 (Sect. 3.1) and optical spectroscopy using both FORS1 multi-object spectrograph and GIRAFFE integral-field unit (IFU) at ESO-VLT (Sect. 3.2). In Appendix A we compare the new H1 data with archival VLA data from Hibbard et al. (1994) and single-dish observations. For the existing VLA data of NGC 5291 and NGC 4694, we refer to B07 and D07, respectively.

3.1. H1 observations

Spectral-line H1 observations were carried out with multiple configurations of the VLA. We used the hybrid DnC, BnC, and BnA configurations to compensate for the foreshortening due to the low declination of NGC 7252 (δ = −24°7). For simplicity, we will refer to them as D, C, and B configurations. In order to achieve a velocity resolution of 2.6 km s^-1 across a velocity range of ~500 km s^-1, we used the correlator in 2AD mode covering a 1.56 MHz-wide band with 128 spectral channels and tuning the two intermediate frequencies (IFs) at different central velocities. One IF was set at ~4825 km s^-1, while the other one was set at ~4570 km s^-1. The two IFs were merged during the data reduction to form a single band centred at 4700 km s^-1. The VLA observing parameters are given in Table 2.

The uv-data were calibrated and combined using AIPS (Greisen 2003) and following standard procedures. Self-calibration was required for each configuration to remove low-level artefacts due to a 1.16 Jy bright source (PKS 2217-251) located to the south of the field at (α2000, δ2000) = (22h20m37.65s, −24°53′58.0″). This continuum source was subtracted using

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Table 1. Galaxy sample.

<table>
<thead>
<tr>
<th>System</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>V_{sys} (km s^{-1})</th>
<th>Dist (Mpc)</th>
<th>L_K (10^{10} L_⊙)</th>
<th>Short description</th>
<th>Bona fide TDGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4694</td>
<td>12 48 15.1</td>
<td>+10 39 01</td>
<td>1160</td>
<td>17</td>
<td>1.5</td>
<td>disturbed lenticular: post-merger</td>
<td>VCC 2062</td>
</tr>
<tr>
<td>NGC 5291</td>
<td>13 47 24.5</td>
<td>−30 24 25</td>
<td>4378</td>
<td>62</td>
<td>14</td>
<td>peculiar lenticular: head-on collision</td>
<td>NGC 5291N, 5291S, 5291SW</td>
</tr>
<tr>
<td>NGC 7252</td>
<td>22 20 44.7</td>
<td>−24 40 42</td>
<td>4792</td>
<td>66.5</td>
<td>17</td>
<td>advanced merger: spiral+spiral</td>
<td>NGC 7252E, 7252NW</td>
</tr>
</tbody>
</table>

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2 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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UV_SUB, after combining the B+C+D data and merging the two IFs. The residual radio continuum was fitted with a first-order polynomial considering line-free channels, which were determined by inspecting channel maps based on the D+C data. The continuum was then removed from the B+C+D data using UVLSF. Some faint residual emission is still observable in several channels at the location of the bright source; this emission was systematically discarded during the masking of the channel maps (described below). The $uv$-data were mapped using multi-scale cleaning (Cornwell 2008; Greisen et al. 2009) and different weighting schemes: (i) robust (RO) weighting (Briggs 1995) with the RO parameter set to 0.5, giving a beam size of $15.8'' \times 10.7''$; and (ii) natural (NA) weighting, giving a beam size of $21.1'' \times 17.8''$.

After the Fourier transform, the H I cubes were analysed using the Groningen Imaging Processing System (Gipsy, Vogelaar & Terlouw 2001). Total H I maps were built by summing masked channel maps. After various trials, we used a mask obtained by smoothing the cubes to $25''$ in space and $12.5$ km s$^{-1}$ in velocity, and clipping at $2.5\sigma$, (where $\sigma$ is the rms noise in the smoothed cube). Velocity fields were built from masked channel maps estimating an intensity-weighted mean velocity. Since the H I line profiles are complex and asymmetric, these velocity fields provide only an overall view of the H I kinematics. Our kinematical analysis is based on full 3D models of the observations, as we describe in Sect. 5.1.

### 3.2. Optical spectroscopy

Optical spectroscopy was obtained as part of several observing runs at ESO facilities. For both NGC 7252 NW and NGC 7252 E, low-resolution long-slit spectra (covering the 4500–7500 Å wavelength domain) were obtained in July 1994 with the red channel of the EMMI camera installed on the New Technology Telescope (NTT) at ESO/La Silla. Details on observing conditions and data reduction are given in Duc & Mirabel (1998). The spectrum of NGC 7252 NW is shown in Fig. 2 (grey line).

New observations were carried out in September 2000 with the FORS1 multi-object spectrograph installed on the Unit Telescope 1 (UT1) of the VLT. We simultaneously obtained the spectra of 19 objects, including NGC 7252 E and NGC 7252 NW. The position angle of the slit-lets was fixed to $72.9^\circ$. We used grism 600B (1.2 Å per pixel) with a total exposure time of $4 \times 1800$ s. The resulting spectrum has higher spectral resolution and sensitivity than the EMMI one, but only covers the wavelength domain 3700–5500 Å. Data reduction was carried out using IRAF. The spectrum of NGC 7252 NW is shown in Fig. 2 (black line). Spectrophotometric data and resulting metalicities are discussed in Sect. 4.2 and listed in Table 5. As is common practice, the line intensities are normalised relative to H$\alpha = 100$ and the errors are estimated using the IRAF splot procedure which relies on Poisson statistics.

We also obtained IFU observations of NGC 7252 NW to investigate its H$\alpha$ kinematics. We used GIRAFFE on the UT2 of the VLT (Pasquini et al. 2002), obtaining 55 exposures of $\sim 23$ min each. The observations are summarised in Table 3. The data were reduced using the ESO pipeline. Additionally, we corrected each reduced cube to heliocentric velocity, before combining all 55 exposures into a variance-weighted mean cube. This final cube was then inspected and analysed using Gipsy. To isolate the H$\alpha$ emission, we subtracted the continuum in the wavelength range 6650–6680 Å, avoiding [N II] emission lines. The continuum was determined by fitting a first-order polynomial to line-free channels bordering the H$\alpha$ line. A total H$\alpha$ map was built by integrating the cube in velocity and clipping at $3\sigma$.

### 4. New results for NGC 7252

In the following we describe the results from the new multiwavelength observations of NGC 7252. Specifically, we use (i) H$\alpha$ data at $25''$ resolution to study the overall gas distribution and kinematics; (ii) long-slit optical spectroscopy to determine the metallicity of several H II regions along the tails; and (iii) IFU spectroscopy to investigate the H$\alpha$ kinematics of the TDG to the north-west.

#### 4.1. H$\alpha$ distribution and kinematics

Figure 3 (top panel) shows an $R$-band image of NGC 7252 overlaid with the total H$\alpha$ map at $25''$ resolution. In agreement with Hibbard et al. (1994), we find that the H I gas is mostly located in the outer regions of the system. The H I tails closely follow the stellar tails and are more extended than the stellar tails in
Fig. 3. Overview of the new H I observations of NGC 7252. Top: total H I map at 25" resolution overlaid on the ESO MPG R-band image. Contours are at 0.3 (≈3σ), 0.6, 1.2, and 2.4 $M_\odot$ pc$^{-2}$. The H I beam is shown to the bottom-right. The bar to the bottom-left corresponds to 20 kpc. Middle: H I velocity field at 25" resolution. The crosses mark the location of the putative TDGs. The dashed lines show the path followed to obtain the PV diagrams. Bottom: PV diagrams along the east tail (left) and north-west tail (right). The vertical lines correspond to the crosses in the velocity field. Contours range from 2σ to 8σ in steps of 1σ = 0.7 mJy beam$^{-1}$. See Sect. 4.1 for details.
Table 4. Properties of NGC 7252 and its tidal tails.

<table>
<thead>
<tr>
<th>Component</th>
<th>H I velocities (km s(^{-1}))</th>
<th>(M_{\text{HI}}) (10(^8) M(_{\odot}))</th>
<th>(M_{\text{H}<em>2}) (10(^8) M(</em>{\odot}))</th>
<th>(L_8) (10(^8) L(_{\odot}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remnant</td>
<td>4596−4618</td>
<td>0.25</td>
<td>3.5</td>
<td>51.6</td>
</tr>
<tr>
<td>ET</td>
<td>4745−4835</td>
<td>2.0</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>NWT</td>
<td>4660−4830</td>
<td>3.2</td>
<td>&gt;0.02</td>
<td>2.9</td>
</tr>
<tr>
<td>Global</td>
<td>4596−4837</td>
<td>5.45</td>
<td>&gt;3.52</td>
<td>55.4</td>
</tr>
</tbody>
</table>

Notes. The H I mass and velocities of the remnant refer to the so-called Western Loop (see Fig. A.1). Molecular masses are calculated assuming \(X_{\text{OII}} = 2.0 \times 10^{-19}\) (cm\(^{-3}\)/K km s\(^{-1}\)) and using the CO fluxes from Dupraz et al. (1990) and Braine et al. (2001). For the NWT the molecular mass is a lower limit because single-dish observations cover only a fraction of the tail. \(B\) luminosities are taken from Hibbard et al. (1994) and rescaled to a distance of 66.5 Mpc.

The H I mass is a lower limit because single-dish observations cover only a fraction of the tail. The ET and NWT display a regular velocity gradient (dashed lines on the velocity diagrams). In the NWT, the HI velocity gradient is not a cutaneous TDGs and other H I regions along the tidal tails. Direct estimates of the oxygen abundance depend on the electron temperature of the ionised gas, which is probed by the [OIII] line at 4363 Å. Unfortunately, this weak line could not be detected in any of our spectra, thus we estimate oxygen abundances using semi-empirical methods.

For the EMMI red spectra, the oxygen abundance can be estimated from the [N II]/H\(_\alpha\) flux ratio. We adopt the calibration of Denicoló et al. (2002) and find 12 + log(O/H) = 8.6 ± 0.1 for both TDGs. For the FORS1 blue spectra, we use the \(R_23\) method involving the [O II], [O III], and H\(_\beta\) lines (after correcting all fluxes for internal extinction using the H\(_\beta\)/H\(_\gamma\) decrement). We adopt the independent \(R_23\) calibrations of McGaugh (1991), as updated by Kuzio de Naray et al. (2004), and Pilyugin (2000). The \(R_23\) method is degenerate and gives two values of the abundance for one observable. This degeneracy is broken by the [N II]/[O II] ratio (McGaugh 1994). This line-ratio is only available for NGC 7252NW and clearly indicates that the higher abundance is the correct one. The resulting abundance is remarkably consistent with that from the [N II]/H\(_\alpha\) method (see Table 5). The high metallicities confirm that both TDG candidates are not pre-existing dwarfs, but they are currently forming out of pre-enriched material ejected from the progenitor galaxies.

Using additional spectra from the FORS1 run, we estimate metallicities at two other locations: a giant H I region near the tip of the ET and one H II knot to the west of NGC 7252. We find oxygen abundances ranging between 8.65 and 8.8, as summarised in Table 5. The metallicities appear to be uniform along the tidal tails and close to the solar value, with no evidence of strong gradients over distances of 80 kpc from the remnant. For comparison, the metallicity in the outskirts of isolated spiral galaxies may show gradients of several dex and reach 1/10 Z\(_\odot\) (Ferguson et al. 1998). This suggests that radial gas mixing occurs during galaxy mergers, in agreement with numerical simulations (Rupke et al. 2010a; Montuori et al. 2010) and recent observations (Kewley et al. 2010; Rupke et al. 2010b; but see also Werk et al. 2011). The latter work emphasises the gas dilution due to the transportation of metal-poor gas from the outskirts to the inner regions. Here, instead, we have evidence of an outwards gas transfer, where metal-rich gas has been brought to the outer regions.

4.3. H\(_\alpha\) kinematics of NGC 7252NW

For NGC 7252NW we also obtained IFU spectroscopy of the H\(_\alpha\) line (Sect. 3.2). The GIRAFFE field of view covers only the innermost region of NGC 7252NW, corresponding to the peak of the H\(_\alpha\) distribution (see Fig. 4, left panel). Since the VLT has a pointing accuracy of ~3′′, the astrometry was determined assuming that the H\(_\alpha\) emission spatially coincides with the R-band emission, as suggested by their similar morphologies (see Fig. 4, middle panel). The H\(_\alpha\) redistribution is elongated towards the North-South direction and shows two peaks separated by ~3′′.

The H\(_\alpha\) emission is resolved in both space and velocity, but it does not show a coherent kinematic structure. Figure 4 (right panel) shows a PV diagram obtained along the two H\(_\alpha\) peaks (dashed line in Fig. 4, middle panel). The H\(_\alpha\) line profiles are broad: the main H\(_\alpha\) peak has a FWHM of ~80 km s\(^{-1}\) (more than twice the H I linewidth), while the average FWHM over the entire field is ~45 km s\(^{-1}\). The central velocity of the main H\(_\alpha\) peak (~4665 km s\(^{-1}\)) is significantly lower than the H I systemic velocity of NGC 7252NW (4678 ± 3 km s\(^{-1}\)), but it is consistent with the H I velocities on its approaching side. The H\(_\alpha\) emission, indeed, does not coincide with the dynamical centre of NGC 7252NW but is shifted towards the Western, approaching side (see cross in Fig. 4, middle panel). In general, the ionized...
gas appears more asymmetric and disturbed than the H I gas. Most likely, we are observing H II regions dominated by turbulence and/or non-circular motions due to stellar feedback.

### 5. Dynamics of Tidal Dwarf Galaxies

In the following, we investigate the internal dynamics of the six TDGs in our sample using high-resolution H I cubes (see Table 6). These cubes are obtained using robust weighting during the Fourier transform and have higher resolutions than those obtained with natural weighting (Sect. 3.1), but at a slight cost in terms of signal-to-noise ratio (S/N). Figures 5 to 10 provide an overview of each TDG: top panels show an optical image (left), a total H I map (middle), and a H I velocity field (right); bottom panels show PV diagrams along the major and minor axes from the observed cube (left), a model cube (middle; see Sect. 5.1), and a residual cube (right). The H I maps were built by integrating the cube over a narrow velocity range (corresponding to the kinematically decoupled velocity gradients) and clipping at 1σ. The H I velocity fields were built by estimating an intensity-weighted-mean velocity considering the same narrow spectral range, and clipping at 3σ.

#### Table 5. Spectrophotometric data and resulting metallicities in the tidal tails of NGC 7252.

<table>
<thead>
<tr>
<th>Region</th>
<th>NGC 7252NW</th>
<th>NGC 7252E</th>
<th>H II–ET</th>
<th>H II–W</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA(J2000)</td>
<td>22° 20′ 33.6″</td>
<td>22° 20′ 56.1″</td>
<td>22° 20′ 59.3″</td>
<td>22° 20′ 41.2″</td>
</tr>
<tr>
<td>Dec(J2000)</td>
<td>−24′ 37″ 24″</td>
<td>−24′ 37″ 9″</td>
<td>−24′ 41″ 11″</td>
<td>−24′ 40″ 45″</td>
</tr>
<tr>
<td>[OII]3727</td>
<td>331 ∓ 66</td>
<td>...</td>
<td>237 ± 40</td>
<td>256 ± 49</td>
</tr>
<tr>
<td>Hα</td>
<td>28 ± 5</td>
<td>...</td>
<td>28 ± 5</td>
<td>24 ± 4</td>
</tr>
<tr>
<td>Hγ</td>
<td>47 ± 5</td>
<td>...</td>
<td>52 ± 6</td>
<td>47 ± 5</td>
</tr>
<tr>
<td>Hβ</td>
<td>100 ± 2</td>
<td>100 ± 6</td>
<td>100 ± 5</td>
<td>100 ± 2</td>
</tr>
<tr>
<td>[OIII]5007</td>
<td>37 ± 2</td>
<td>53 ± 5</td>
<td>−41 ± 5</td>
<td>29 ± 2</td>
</tr>
<tr>
<td>[NII]6584</td>
<td>109 ± 4</td>
<td>150 ± 9</td>
<td>125 ± 5</td>
<td>89 ± 4</td>
</tr>
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<td>...</td>
</tr>
<tr>
<td>[NII]6584</td>
<td>285 ± 30</td>
<td>233 ± 28</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>[SII]6717</td>
<td>62 ± 10</td>
<td>58 ± 11</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>[SII]6731</td>
<td>51 ± 10</td>
<td>42 ± 8</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>[SII]6717</td>
<td>33 ± 9</td>
<td>33 ± 9</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>[OII]3727</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
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<tr>
<td>[OIII]5007</td>
<td>3.6 ± 0.5</td>
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<tr>
<td>[NII]6584</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
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<tr>
<td>[SII]6717</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
</tr>
<tr>
<td>[SII]6731</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
<td>3.6 ± 0.5</td>
</tr>
</tbody>
</table>

#### Table 6. Properties of the high-resolution H I datacubes.

<table>
<thead>
<tr>
<th>System</th>
<th>Beam (asec × asec)</th>
<th>PA (°)</th>
<th>ΔV (km s⁻¹)</th>
<th>rms noise (mJy beam⁻¹)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4694</td>
<td>14.7 × 14.3</td>
<td>−70.65</td>
<td>7.3</td>
<td>0.6</td>
<td>a</td>
</tr>
<tr>
<td>NGC 5291</td>
<td>8.0 × 8.0</td>
<td>45.76</td>
<td>10.6</td>
<td>0.5</td>
<td>b</td>
</tr>
<tr>
<td>NGC 7252</td>
<td>15.8 × 10.7</td>
<td>62.96</td>
<td>10.6</td>
<td>0.6</td>
<td>c</td>
</tr>
</tbody>
</table>

**Notes.** To increase the signal-to-noise ratio, the robust cube of NGC 5291 (with a beam 6.6″ × 4.36″) has been smoothed to 8″ × 8″, whereas the robust cube of NGC 7252 has been smoothed in velocity to ~10.6 km s⁻¹.

**References.** (a) Duc et al. (2007); (b) Bournaud et al. (2007); (c) this work.
contamination from the underlying HI debris. Despite these limitations, the HI morphology and kinematics resemble a rotating disc. These putative discs are studied in detail in the next section using 3D kinematical models.

5.1. Kinematical models

To test the hypothesis that TDGs are associated with an HI disc, we built 3D kinematical models following similar procedures as Lelli et al. (2012a,b, 2014b). As a first step, we inspected channel maps and PV diagrams to obtain initial estimates of the dynamical centre \((x_0, y_0)\), position angle (PA), inclination (i), systemic velocity \((V_{\text{sys}})\), and rotation velocity \((V_{\text{rot}})\). These initial estimates were then used as inputs to build model cubes and subsequently refined iteratively until we obtained a model cube that closely matches the observed cube. Given the low S/N and possible contamination from the underlying HI debris, the best models were not determined by a blind \(\chi^2\) minimization, but by visual inspection of channel maps and PV diagrams.

Fig. 5. Top panels: optical image (left), total HI map (middle), and HI velocity field (right). The dashed ellipse corresponds to the disc model described in Sect. 5.1. The cross and dashed line illustrate the kinematical centre and major axis, respectively. In the bottom-left corner, we show the linear scale (optical image) and the HI beam (total HI map and velocity field) as given in Table 6. In the total HI map, contours are at ∼4.5, 9, 13.5, 18, and 22.5 \(M_\odot\) pc\(^{-2}\). Bottom panels: PV diagrams obtained from the observed cube (left), model cube (middle), and residual cube (right) along the major and minor axes. Solid contours range from 2\(\sigma\) to 8\(\sigma\) in steps of \(1\sigma\). Dashed contours range from −4\(\sigma\) to −8\(\sigma\) in steps of −2\(\sigma\). The horizontal and vertical lines correspond to the systemic velocity and dynamical centre, respectively.
Fig. 6. Same as Fig. 5 for NGC 5291S. In the total HI map, contours are at $\sim 4.5, 9, 13.5, \text{ and } 18 \, M_\odot \, \text{pc}^{-2}$.

The initial models are built assuming a thin disc with an exponential surface density profile, a flat rotation curve, and a constant HI velocity dispersion ($\sigma_{\text{HI}}$). The disc is projected on the sky (according to the values of $x_0, y_0, \text{PA}, i, \text{ and } V_{\text{sys}}$) to generate a model cube, which is subsequently smoothed to the same spatial and spectral resolutions of the observations. Finally, the model cube is renormalised on a pixel-by-pixel basis to the observed HI map, i.e. we reproduce the asymmetric gas distribution by imposing that, at every spatial pixel, the flux along each HI line profile in the model cube is equal to that of the corresponding line profile in the observations (see Lelli et al. 2012a,b, for details). As a result of this normalization, the assumption of an exponential HI surface density profile has little effect on the final model, but is still useful to (i) reproduce beam-smearing effects due to a varying HI flux on spatial scales smaller than the HI beam; and (ii) obtain an estimate of $i$ by comparing model HI maps (before normalization) to the observed HI maps (see dashed ellipses on the top-middle panels of Figs. 5 to 10). For VCC 2062, the model cube was not normalised to the observed HI map because two distinct kinematic components overlap in both space ($R \approx 15''$ to $30''$ towards the south-west) and velocity ($V_{\text{l.o.s.}} \approx 1110$ to $1160 \, \text{km s}^{-1}$); a simple exponential disc model allows disentangling these two kinematic components (see Fig. 10).

Once the geometrical parameters of the HI disc are fixed, the free parameters of the model are $\sigma_{\text{HI}}, V_{\text{rot}}$, and the outermost
Fig. 7. Same as Fig. 5 for NGC 5291SW. In the total HI map, contours are at $\sim 4.5, 9, \text{ and } 13.5 \, M_\odot \, \text{pc}^{-2}$.  

5.1.1. Comparing models and observations

The bottom panels of Figs. 5 to 10 compare PV diagrams from the observed cubes and the model cubes. For all six TDGs, a rotating disc with axisymmetric kinematics can reproduce the H I velocity gradient along the major axis. The H I emission along the minor axis is also well reproduced, suggesting that any non-circular motion should be relatively small. Some radial motions may be present in NGC 5291N and VCC 2062, as hinted to by the tilt of their minor-axis PV diagrams. For these two objects, we built additional models including a global radial component ($V_{\text{rad}}$). It is unclear whether the inclusion of $V_{\text{rad}}$ substantially improves the models, but we can constrain the ratio $V_{\text{rad}}/V_{\text{rot}}$ to be smaller than 0.3. Hence, the disc kinematics is dominated by rotation and radial motions can be neglected to a first approximation. We stress that the inclusion of $V_{\text{rad}}$ has no effect on the measured values of $V_{\text{rot}}$. The quality of our modelling is further demonstrated in Appendix C, where we compare H I channel maps from the observed cubes and the model cubes.
In general, our initial estimates of the kinematical parameters gave a good description of the observations, but we have also built models with different parameter values to estimate the corresponding uncertainties. The parameters of the final models are listed in Table 7. For $\sigma_{\text{HI}}$, we find typical values between 7 and 12 km s$^{-1}$ apart from NGC 5291N and NGC 5291S. For these two TDGs, a velocity dispersion of $\sim$20 km s$^{-1}$ is required to reproduce the observed cube: this high value may be either physical (high turbulence in the ISM) or due to unresolved non-circular motions within the beam. In NGC 5291 a higher turbulence may be expected because the H1 ring is the result of a fast head-on collision with a massive companion.

Although a rotating disc provides a good description of the H1 kinematics, there is an important issue with this model. The orbital times at the outer edge of the disc ($t_{\text{orb}}$) are much longer than the estimated ages of the TDGs, implying that the discs would have undergone less than a full orbit. In Table 7, we provide both $t_{\text{orb}}$ and the ratio $t_{\text{merg}}/t_{\text{orb}}$, where $t_{\text{merg}}$ is the characteristic dynamical time of the interaction/merger event. In particular, we assume that (i) the H1 ring around NGC 5291 has formed $\sim$360 Myr ago (B07); (ii) the progenitor galaxies forming NGC 7252 fell together $\sim$700 Myr ago (Hibbard & Mihos 1995; Chien & Barnes 2010); and (iii) the interaction/merger forming VCC 2062 and NGC 4694 has happened between 0.5

Fig. 8. Same as Fig. 5 for NGC 7252E. In the total H1 map, contours are at $\sim$1.5, 3.0, and 4.5 $M_\odot$ pc$^{-2}$. 
**Fig. 9.** Same as Fig. 5 for NGC 7252NW. In the total H I map, contours are at $\sim 1.5, 3.0, 4.5,$ and $6 M_\odot$ pc$^{-2}$.

**Table 7.** Properties of the TDGs from 3D kinematical models.

<table>
<thead>
<tr>
<th>Object</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>$V_{sys}$ (km s$^{-1}$)</th>
<th>PA (°)</th>
<th>$i$ (°)</th>
<th>$R_{out}$ (kpc)</th>
<th>$V_{out}$ (km s$^{-1}$)</th>
<th>$\sigma_{HI}$ (km s$^{-1}$)</th>
<th>$t_{orb}$ (Gyr)</th>
<th>$t_{max}/t_{orb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 5291N</td>
<td>13 47 20.3</td>
<td>$-30 20 54$</td>
<td>4150</td>
<td>0</td>
<td>55</td>
<td>4.8 $\pm$ 1.2</td>
<td>40 $\pm$ 9</td>
<td>20 $\pm$ 2</td>
<td>0.7 $\pm$ 0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>NGC 5291S</td>
<td>13 47 22.7</td>
<td>$-30 27 40$</td>
<td>4660</td>
<td>5</td>
<td>65</td>
<td>7.2 $\pm$ 1.2</td>
<td>20 $\pm$ 6</td>
<td>20 $\pm$ 2</td>
<td>2.2 $\pm$ 0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>NGC 5291SW</td>
<td>13 47 17.1</td>
<td>$-30 28 21$</td>
<td>4688</td>
<td>50</td>
<td>60</td>
<td>4.8 $\pm$ 1.2</td>
<td>22 $\pm$ 7</td>
<td>12 $\pm$ 2</td>
<td>1.3 $\pm$ 0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>NGC 7252E</td>
<td>22 20 56.0</td>
<td>$-24 41 10$</td>
<td>4815</td>
<td>100</td>
<td>80</td>
<td>4.5 $\pm$ 1.9</td>
<td>11 $\pm$ 5</td>
<td>10 $\pm$ 2</td>
<td>2.5 $\pm$ 1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>NGC 7252NW</td>
<td>22 20 33.7</td>
<td>$-24 37 24$</td>
<td>4678</td>
<td>125</td>
<td>60</td>
<td>7.7 $\pm$ 1.9</td>
<td>16 $\pm$ 6</td>
<td>10 $\pm$ 2</td>
<td>3.0 $\pm$ 1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>VCC 2062</td>
<td>12 48 00.8</td>
<td>+10 58 15</td>
<td>1152</td>
<td>55</td>
<td>45</td>
<td>2.6 $\pm$ 0.6</td>
<td>13 $\pm$ 7</td>
<td>7 $\pm$ 1</td>
<td>1.2 $\pm$ 0.5</td>
<td>0.4--0.8</td>
</tr>
</tbody>
</table>

**Notes.** (∗) These high values of $\sigma_{HI}$ may be either physical or due to unresolved non-circular motions within the H I beam.
and 1 Gyr ago. Note that $t_{\text{merg}}$ is a hard upper limit for the TDG ages, since it takes time for the tidal debris to be ejected and for the gas within them to collapse under self-gravity. It is unclear, therefore, whether the H I discs associated with the TDGs have had enough time to reach dynamical equilibrium. This issue is further discussed in Sect. 6.1 with the aid of numerical simulations.

Motivated by the long orbital times, we have explored alternative models and found that a collision between two large H I clouds could also reproduce the H I data. These models, however, need to be highly fine-tuned, given that the two H I clouds must have sizes, spatial separation, and velocity separation mimicking the symmetric sides of a rotating disc. This scenario, therefore, appears contrived. We conclude that we are likely observing the formation of rotating H I discs in the nearby Universe.

5.1.2. Model assumptions and uncertainties

Dwarf galaxies can show both flat and rising rotation curves (e.g. Swaters et al. 2009; Lelli et al. 2012a, b, 2014b; Oh et al. 2015). We assume that $V_{\text{rot}}$ is constant with $R$ to minimise the number of free parameters in our models. This assumption has little effects on our results because we are interested in the rotation velocity at the outermost radius ($V_{\text{rot}}$). The actual shape of the rotation curve is difficult to determine due to the low number of resolution elements ($\lesssim 4$ beams along the disc major axis): in this situation a flat rotation curve produces similar model cubes.

---

**Fig. 10.** Same as Fig. 5 for VCC 2062. In the total H I map, contours are at $\sim 1.5, 3.0, 4.5, 6$, and $7.5 M_\odot$ pc$^{-2}$. 
as a solid-body one (cf. Lelli et al. 2012a, Fig. 5, second row). As a further test, we built additional models assuming a solid-body rotation curve (see Appendix D). For NGC 5291N and NGC 7252NW, a flat rotation curve is preferable to a solid-body one, as indicated by the observed H I emission at high rotation velocities near the disc centre. For all TDGs, solid-body and flat rotation curves return similar values of \( V_{\text{rot}} \) but there is a weak systematic effect leading to higher \( V_{\text{rot}} \) for solid-body rotation curves by \( \sim 2 \text{–} 3 \text{~km~s}^{-1} \). This is well within our assumed errors. Hence, the dynamical masses estimated in Sect. 5.2 are largely independent of the assumed rotation curve shape.

The uncertainties on \((\sigma_0, y_0, \text{PA})\), \( V_{\text{sys}} \), and \( V_{\text{rot}} \) have negligible effect on the measured values of \( V_{\text{rot}} \). PV diagrams from model cubes and observed cubes show that these parameters have been properly determined (see Figs. 5 to 10, bottom panels). The value of \( i \) requires special attention because \( V_{\text{rot}} \propto V_{\text{los}}/\sin(i) \), where \( V_{\text{los}} \) is the projected velocity along the line of sight. We constrain the values of \( i \) by comparing model H I maps (before pixel-to-pixel renormalization) to the observed H I maps (see dashed ellipses in Figs. 5 to 10). In general, we find that inclinations higher/lowoer than the assumed ones by \( \sim 30^\circ \) are excluded by the data. This is conservatively considered as a 2\( \sigma \) error. The error \( \sigma_{V_{\text{rot}}} \) on \( V_{\text{rot}} \) is then given by

\[
\sigma_{V_{\text{rot}}} = \sqrt{\left[ \sigma_{V_{\text{rot}}} \sin(i) \right]^2 + \left[ V_{\text{rot}} \sigma_i \tan(i) \right]^2} \tag{1}
\]

where \( \sigma_i = 15^\circ \) and \( \sigma_{V_{\text{rot}}} \) is estimated as half the velocity resolution of the observations.

5.2. Mass budget

In the previous section, we showed that rotating disc models provide a good description of the H I gas associated with TDGs. It is unclear, however, whether these H I discs are in dynamical equilibrium, given that they did not have enough time to complete a full orbit since the interaction/merger event. In the following, we assume that the TDGs in our sample are in dynamical equilibrium and estimate their dynamical masses from the H I rotation velocities. The inferred dynamical masses are then compared with the observed baryonic masses to determine the DM content of TDGs. As we discuss in Sect. 6.1, numerical simulations suggest that these dynamical masses may be quite reliable despite the long orbital times.

5.2.1. Dynamical mass

For the TDGs in our sample, the rotation velocities \( (V_{\text{rot}}) \) are comparable with the H I velocity dispersions \( (\sigma_{\text{HI}}) \), thus the former must be corrected for pressure support in order to trace the gravitational potential. We apply the asymmetric-drift correction using the following equation:

\[
V_{\text{circ}} = \sqrt{V_{\text{rot}}^2 + \sigma_{\text{HI}}^2 (R/h_{\text{HI}})}, \tag{2}
\]

where \( V_{\text{circ}} \) is the circular velocity tracing the potential well. This equation assumes that (i) the velocity dispersion is isotropic; (ii) the velocity dispersion and scale height of the disc are constant with radius; and (iii) the H I surface density profile is an exponential function with scale length \( h_{\text{HI}} \) (see Appendix A of Lelli et al. 2014a, for details). Using 3D disc models, we estimate that our TDGs have \( R_{\text{out}}/h_{\text{HI}} \approx 2 \), where \( R_{\text{out}} \) is the outermost radius of the H I disc. The dashed ellipses in Figs. 5 to 10 (top-middle panels) show the model H I maps at \( R = 2h_{\text{HI}} \) (before being renormalised to the observed HI map, see Sect. 5.1). The only exception is NGC 5291N, which have \( R_{\text{out}} \approx 3h_{\text{HI}} \).

The dynamical mass within \( R_{\text{out}} \) is then given by

\[
M_{\text{dyn}} = \epsilon \frac{R_{\text{out}} V_{\text{circ}}^2}{G} \tag{3}
\]

where \( G \) is Newton’s constant and \( \epsilon \) is a parameter of the order of unity that depends on the 3D distribution of the total mass. For simplicity, we assume \( \epsilon = 1 \) (spherical geometry). For a thin exponential disc, one can calculate that \( \epsilon \approx 0.95 \) at \( R = h \) and \( \epsilon \approx 0.77 \) at \( R = 2h \) (cf. Freeman 1970). The resulting dynamical masses are given in Table 8. Besides the uncertainty due to the dynamical equilibrium of TDGs, the uncertainty on \( M_{\text{dyn}} \) is driven by errors on \( V_{\text{circ}} \) and \( R_{\text{out}} \). The former error is estimated using Eq. (1), while the latter is conservatively estimated as half the spatial resolution of the HI data.

5.2.2. Baryonic mass

The baryonic mass of a galaxy (\( M_{\text{bar}} \)) is given by three main components (e.g. McGaugh 2012): atomic gas (\( M_{\text{atom}} \)), molecular gas (\( M_{\text{mol}} \)), and stars (\( M_{\star} \)). In TDGs \( M_{\text{atom}} \) largely dominates the baryonic mass budget, thus the uncertainties on \( M_{\star} \) and \( M_{\text{mol}} \) due to the choice of, respectively, a stellar mass-to-light ratio \( (\Upsilon_{\star}) \) and CO-to-H2 conversion factor \( (X_{\text{CO}}) \) have minimal impact. On the other hand, measuring \( M_{\text{atom}} \) is not straightforward because TDGs are still embedded within gas-rich tidal debris. It is reasonable to assume that all the H I gas within \( R_{\text{out}} \) is associated with the TDGs, since they represent a local potential well that “clears out” the gas from the surroundings. The values of \( M_{\text{at}om} \) in Table 8 are based on this assumption and adopt a typical error of 10% (the H I masses are multiplied by a factor of 1.37 to take the contributions of helium and heavier elements into account). Alternatively, one may assume that, at the TDG location, some gas is associated with the underlying tidal debris. In the extreme hypothesis that tidal debris have a uniform H I surface density of \( 1 \ M_{\odot} \text{pc}^{-2} \) over the TDG area, the values of \( M_{\text{at}om} \) in Table 8 would decrease by \( \sim 30\% \) to 40%.

As we discussed in previous sections, TDGs have higher metallicities than typical dwarfs, thus CO lines are readily detected and H2 masses can be estimated using a typical value of \( X_{\text{CO}} = 2.0 \times 10^{20} \text{ cm}^2 \text{(K km s}^{-1}\text{)}^{-1} \). For three TDGs (NGC 5291N, NGC 5291S, and NGC 7252NW), we use the molecular masses from Braine et al. (2001), rescaled to the distances in Table 1. For VCC 2062, we adopt the molecular mass from D07. For the remaining two TDGs (NGC 5291SW and NGC 7252E), CO observations are not available, thus we estimated \( M_{\text{mol}} \approx 7 \times 10^{-10} \text{ yr}^{-1} \) (Leroy et al. 2008). This is observationally motivated by the results of Braine et al. (2001) for a sample of eight TDGs. For these two TDGs, SFRs are estimated using FUV fluxes from Boquien et al. (2009) and the calibration from Kennicutt & Evans (2012), which is based on Starburst99 models (Leitherer et al. 1999) and a Kroupa initial mass function (Kroupa & Weidner 2003). For all TDGs, we adopt a conservative error of 50% on \( M_{\text{mol}} \) to consider possible variations in \( X_{\text{CO}} \) and/or SFE among galaxies. The molecular masses of these TDGs are from \( \sim 4 \) to \( \sim 30 \) times smaller than \( M_{\star} \), thus they marginally contribute to \( M_{\text{bar}} \).

The stellar masses of TDGs are tricky to estimate because they are formed by a complex mix of young stars (comprising
Table 8. Mass budget in TDGs assuming dynamical equilibrium.

<table>
<thead>
<tr>
<th>Object</th>
<th>(V_{\text{rot}}) (km s(^{-1}))</th>
<th>(M_{\text{dyn}}) (10(^6) (M_\odot))</th>
<th>(M_{\text{dom}}) (10(^8) (M_\odot))</th>
<th>(M_\ast) (10(^8) (M_\odot))</th>
<th>(M_{\text{mol}}) (10(^8) (M_\odot))</th>
<th>(M_{\text{bar}}) (10(^8) (M_\odot))</th>
<th>(M_{\text{sys}}/M_{\text{bar}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 5291N</td>
<td>45 ± 9</td>
<td>23 ± 1</td>
<td>12.3 ± 1.2</td>
<td>1.1 ± 0.5</td>
<td>2.2 ± 1.1</td>
<td>15.6 ± 1.7</td>
<td>1.5 ± 0.7</td>
</tr>
<tr>
<td>NGC 5291S</td>
<td>35 ± 6</td>
<td>20 ± 8</td>
<td>11.8 ± 1.2</td>
<td>0.8 ± 0.4</td>
<td>3.3 ± 1.7</td>
<td>15.9 ± 2.1</td>
<td>1.3 ± 0.5</td>
</tr>
<tr>
<td>NGC 5291SW</td>
<td>28 ± 7</td>
<td>8.7 ± 4.9</td>
<td>4.9 ± 0.5</td>
<td>0.3 ± 0.2</td>
<td>1.9 ± 1.0</td>
<td>7.1 ± 1.2</td>
<td>1.2 ± 0.7</td>
</tr>
<tr>
<td>NGC 7252E</td>
<td>18 ± 5</td>
<td>3.4 ± 2.4</td>
<td>2.9 ± 0.3</td>
<td>0.85 ± 0.43</td>
<td>0.20 ± 0.10</td>
<td>3.9 ± 0.5</td>
<td>0.9 ± 0.6</td>
</tr>
<tr>
<td>NGC 7252NW</td>
<td>21 ± 6</td>
<td>7.9 ± 4.9</td>
<td>7.0 ± 0.7</td>
<td>0.94 ± 0.47</td>
<td>0.22 ± 0.11</td>
<td>8.2 ± 0.8</td>
<td>1.0 ± 0.6</td>
</tr>
<tr>
<td>VCC 2062</td>
<td>16 ± 7</td>
<td>1.5 ± 1.3</td>
<td>0.75 ± 0.07</td>
<td>0.47 ± 0.24</td>
<td>0.23 ± 0.12</td>
<td>1.4 ± 0.3</td>
<td>1.0 ± 0.9</td>
</tr>
</tbody>
</table>

Notes. (** For these two galaxies CO observations are not available, thus \(M_{\text{mol}}\) is indirectly estimated from the SFR assuming that TDGs have the same SFE as spiral galaxies (~ 5 × 10\(^{-10}\) yr\(^{-1}\)). See Sect. 5.2.2 for details.

5.3. Comparison with other dwarf galaxies

To assess whether the DM content of TDGs is really anomalous, we use a control-sample of typical star-forming dwarfs formed by 30 irregulars (Irrs) and 6 blue compact dwarfs (BCDs). The rotation velocities of these galaxies have been measured by Swaters et al. (2009) and Lelli et al. (2014b) building model cubes of the H1 observations, thus they are fully comparable with those derived here. TDGs are heavily gas-dominated \((M_{\text{gas}}/M_\ast \approx 10)\), thus \(M_{\text{dyn}}/M_{\text{bar}}\) is estimated at roughly \(R \approx 2h_{11}\), where \(h_{11}\) is the scale length of the H1 disc (Sect. 5.2). To compute a meaningful comparison with typical dwarfs, we need to compute \(M_{\text{dyn}}/M_{\text{bar}}\) within a similar radius. In general, these galaxies have \(M_{\text{gas}}/M_\ast \leq 1–2\), thus it is more natural to consider the scale length of the stellar disc \(h_\ast\). Given that typical dwarfs have \(h_{11}/h_\ast \approx 1.5\) (cf. Swaters et al. 2002), we estimate \(M_{\text{dyn}}/M_{\text{bar}}\) at \(R \approx 3h_\ast\) (the edge of the stellar disc).

The Irrs are drawn from Swaters et al. (2009) using the following criteria: (i) the galaxies have 30° ≤ \(i\) ≤ 80°; (ii) the H1 rotation curves have quality flag \(q \geq 2\) and are traced out to \(R \approx 3h_\ast\); and (iii) \(V_{\text{rot}} < 100\) km s\(^{-1}\) at the last measured point.

The BCDs are drawn from Lelli et al. (2014b) considering only galaxies with reliable estimates of \(V_{\text{rot}}\) (see their Sect. 7).

Contrary to TDGs, typical dwarfs often have comparable stellar and gaseous masses, thus the values of \(M_{\text{mol}}/M_{\text{bar}}\) strongly depend on the assumed stellar mass-to-light ratio \(\Upsilon_\ast\). For Irrs we compute two different values of \(M_{\text{dyn}}/M_{\text{bar}}\) assuming a “heavy disc” \((\Upsilon_\ast = 2)\) and a “light disc” \((\Upsilon_\ast = 1)\). We do not provide an error bar on \(M_{\text{dyn}}/M_{\text{bar}}\) because this is fully dominated by the assumed variation in \(\Upsilon_\ast\). For BCDs, we use the stellar masses obtained from modelling colour-magnitude diagrams of resolved stellar populations (see Lelli et al. 2014b).

Fig. 11. Mass budget within \(R \approx 3\) h, in different types of dwarf galaxies: Irrs (blue diamonds, from Swaters et al. 2009), BCDs (black squares, from Lelli et al. 2014b), and TDGs (red points). For Irrs \(M_{\text{bar}}\) is estimated assuming both a “heavy disc” with \(\Upsilon_\ast = 2\) (open symbols) and a “light disc” with \(\Upsilon_\ast = 1\) (filled symbols). For BCDs the stellar mass is estimated from colour-magnitude diagrams of resolved stellar populations (see Lelli et al. 2014b).
6. Discussion

In this paper we studied the gas dynamics in a sample of six TDGs. These galaxies have higher metallicities than dwarfs of similar mass and appear kinematically decoupled from the surrounding tidal debris, indicating that they are bona fide TDGs (Sect. 4). We built 3D kinematical models and found that the H1 emission associated with TDGs can be described by rotating discs (Sect. 5.1). The orbital times of these discs, however, are much longer than the merger timescales (as inferred from numerical simulations), indicating that they have undergone less than a full orbit since the TDG formation. This raises the question as to whether TDGs are in dynamical equilibrium and the observed velocities can be used to estimate dynamical masses. If one assumes that these TDGs are in dynamical equilibrium, the inferred dynamical masses are fully consistent with the observed baryonic masses, implying that TDGs are nearly devoid of DM (Sect. 5.2). In the following, we start by scrutinizing the hypothesis of dynamical equilibrium with the aid of numerical simulations. Then, we discuss the implications of our results for the distribution of non-baryonic DM in galaxies and the possible simulations. Finally, we investigate the location of TDGs on the baryonic Tully-Fisher relation (BTFR, McGaugh et al. 2000) and discuss alternative theories like MOND.

6.1. Dynamical equilibrium: clues from numerical simulations

Bournaud & Duc (2006) and B07 presented hydro-dynamical simulations of interacting/merging systems, investigating the detailed process of TDG formation. We have re-analysed the output of these simulations to check the hypothesis that the relaxation time in TDGs could be shorter than the orbital time. For different snapshot of the simulations, we measured (i) the dynamical mass $M_{\text{dyn}}$ of the simulated TDGs inferred from gas rotation curves, i.e. considering the rotation velocities of individual gas particles with respect to the mean spin axis; and (ii) the real mass $M_{\text{real}}$ within the TDG radius, obtained by summing gas, star, and DM particles (the latter ones constitute a negligible amount of mass). For a galaxy in dynamical equilibrium, we expect $M_{\text{dyn}}/M_{\text{real}} = 1$ within ~10% (the typical errors associated with the estimate of $M_{\text{dyn}}$ from simulated gas rotation curves).

In Fig. 12, the ratio $M_{\text{dyn}}/M_{\text{real}}$ is plotted versus the look-back time, where $t = 0$ corresponds to the snapshot of the simulation that reproduces the present-day properties of the observed system. We show two different simulations: TDGs formed in the tidal tails of a standard disc-disc merger (similar to NGC 7252) and TDGs formed in a collisional ring (matching the properties of NGC 5291). These simulated TDGs have dynamical masses comparable to those of observed TDGs (cf. B07). At early times, the values of $M_{\text{dyn}}/M_{\text{real}}$ significantly differ from 1 and display a large scatter, indicating that TDGs are still far from dynamical equilibrium. After a few 100 Myr, however, the scatter substantially decreases and the values of $M_{\text{dyn}}/M_{\text{real}}$ gets closer and closer to 1. This suggests that the simulated TDGs may have reached dynamical equilibrium in less than an orbital time.

For collisionless stellar systems, it is known that the process of relaxation takes a few orbital times, since it occurs through the energy exchange between individual particles and the total gravitational potential evolving over orbital timescales (Lynden-Bell 1967). For collisional gas-dominated systems (such as TDGs), the energy can be exchanged and radiated away on a local crossing time of the order of ~10 Myr (Mac Low 1999). Thus, one may speculate that in collisional gas-rich systems the process of relaxation takes less than one orbital time and is significantly faster than in collisionless ones. Further theoretical studies are needed to understand these processes. It is clear, however, that TDGs provide a unique opportunity to study galaxy relaxation and represent a local benchmark for understanding disc formation in gas-rich galaxies at high redshifts.

6.2. Implications for the DM distribution

Assuming that the TDGs in our sample are in dynamical equilibrium, we deduce that they are devoid of DM as expected from numerical simulations where tidal forces segregate disc material from halo material (Barnes & Hernquist 1992; Bournaud & Duc 2006; Wetzstein et al. 2007). This provides an indirect but empirical confirmation that most DM must be distributed in pressure-supported halos.

Using cosmological simulations, Read et al. (2008, 2009) and Pillepich et al. (2014) argued that spiral galaxies like the Milky Way should possess a rotating disc of non-baryonic DM. This forms because merging satellites tend to be dragged towards the disc plane by dynamical friction and then disrupted by tides, depositing both stars and DM into the disc. Ruchti et al. (2014, 2015) used a chemo-dynamical template to search for accreted stars in the Milky Way and found no evidence for an accreted stellar disc, implying that near-plane mergers have been very rare in our Galaxy during the past ~10 Gyrs. Nonetheless, a “dark disk” may help to explain the vertical kinematics of stars in the solar neighborhood (Bienaymé et al. 2014). Moreover, Fan et al. (2013) and McCullough & Randall (2013) speculated that exotic forms of self-interacting DM can form rotating dark discs as massive as the baryonic ones. The values of $M_{\text{dyn}}/M_{\text{bar}}$ in TDGs shed new light on these putative dark discs, given that any kind of rotation-supported material in the progenitor galaxies may form tidal tails and be accreted in TDGs. Our results imply that either these putative dark discs are significantly less massive than the observed baryonic discs or they are too dynamically-hot to be accreted by TDGs.
6.3. Implications for dark gas

Several observations suggest that a fraction of gas in galaxy discs is not accounted for by H I or CO observations. In the Milky Way, this “dark gas” has been inferred from (i) γ-ray emission due to the collision of cosmic rays with interstellar nucleons (Grenier et al. 2005, Abdo et al. 2010); and (ii) a measured excess of thermal dust emission with respect to a canonical dust-to-gas ratio, as indicated by FIR/submm maps from IRAS (Reach et al. 1994), COBE (Reach et al. 1998), and Planck (Planck Collaboration XIX 2011). Both techniques indicate that, in the Milky Way, the dark gas mass is comparable to the CO-traced molecular mass. The relative mass of dark gas may be even larger in the LMC (Galliano et al. 2011). This dark gas may consist of optically thick H I and/or H 2 in the outer regions of molecular clouds, where CO is photodissociated (Wolfire et al. 2010; Glover et al. 2010). TDGs offer a unique way to probe dark gas in galaxies outside the Local Group, given that this undetected baryonic component would give values of $M_{\text{dyn}}/M_{\text{bar}} > 1$. Unfortunately, our current estimates of $M_{\text{dyn}}/M_{\text{bar}}$ are not precise enough to identify any potential contribution from dark gas at the expected level.

Pfneniger et al. (1994) and Pfenniger & Combes (1994) proposed very cold molecular gas as an alternative to non-baryonic DM in galaxies. This putative dark gas would consist of small “clumpuscules” that do not emit any detectable line and are not associated with star formation. Intriguingly, the observed rotation curves of disc galaxies can be well reproduced simply by scaling up the observed contributions of stars and gas (Hoekstra et al. 2001; Swaters et al. 2012). This very cold molecular gas has also been supported by other dynamical arguments such as the existence of spiral patterns and long-lived warps in the outer regions of H I discs (Bureau et al. 1999; Masset & Bureau 2003; Revaz & Pfenniger 2004; Revaz et al. 2009). These H 2 clumpuscules should end up in TDGs and be detected as a significant excess of dynamical mass over the baryonic one. In contrast with B07, our current results do not support the existence of large numbers of cold H 2 clumpuscules in excess of the more modest expectation for “standard” dark gas.

6.4. The baryonic Tully-Fisher relation and MOND

Figure 13 shows the location of TDGs on the BTFR. We use data from McGaugh (2005) for star-dominated galaxies and McGaugh (2012) for gas-dominated ones. TDGs are systematically shifted to the left side of the BTFR. This is not fully surprising since these TDGs seem to have smaller DM content due to the collision of cosmic rays with interstellar nucleons (EFE, Bekenstein & Milgrom 1984). The numerical simulations discussed in Sect. 6.1 suggest that TDGs may reach the expected level.

But it remains unclear whether this would still hold in MOND. Hydrodynamical simulations in MOND are needed to clarify this issue.

If MOND is interpreted as modified gravity, the strong equivalence principle is violated and the internal dynamics of a system can be affected by an external gravitational field (Bekenstein & Milgrom 1984). We define $g_{\text{Ni}} = GM_{\text{host}}/R_{\text{out}}^2$ as the internal Newtonian acceleration of the TDG. We also define $g_{\text{Ne}} = GM_{\text{host}}/D_{\text{p}}^2$ as the external Newtonian acceleration, where $M_{\text{host}}$ is the baryonic mass of the central galaxy remnant and $D_{\text{p}}$ is the projected distance to the TDGs. $M_{\text{host}}$ is estimated as $L_K / \Upsilon_K$, where $L_K$ is given in Table 1 and $\Upsilon_K = 0.6 M_\odot / L_\odot$ (McGaugh & Schombert 2015). The values of $g_{\text{Ni}}$ and $g_{\text{Ne}}$ are given in Table 9. They are roughly comparable, hence the EFE may be important.

To a first approximation, the EFE can be described by Eq. (60) of Famaey & McGaugh (2012): 3

$$a_i = g_{\text{Ni}} \left( \frac{q_{\text{Ni}} + q_{\text{Ne}}}{a_0} \right) + g_{\text{Ne}} \left[ \left( \frac{q_{\text{Ni}} + q_{\text{Ne}}}{a_0} \right)^{\frac{1}{n}} - \left( \frac{q_{\text{Ni}}}{a_0} \right)^{\frac{1}{n}} \right],$$

(4)

where $a_i = V_i^2 / R$ is the internal acceleration of the TDG, $a_0 = 1.3 \times 10^{-8}$ cm s$^{-2}$ is the MOND acceleration scale, and $\nu(y)$ is the interpolation function. Following McGaugh (2008), we assume $\nu(y) = 1 / (1 - [1 - \exp(-y^{1/2})]^{1/n})$, where the cases $n = 1$ and $n = 2$ nearly correspond to the so-called “simple” and “standard” functions, respectively. In Table 9 we provide the velocities expected

3 This equation derives from the quasi-linear formulation of MOND (Milgrom 2010). We have also considered the non-linear formulation of Bekenstein & Milgrom (1984) using Eq. (59) of Famaey & McGaugh (2012) and adopting the simple interpolation function. We find consistent results within $\sim 1$ km s$^{-1}$.

Fig. 13. Location of TDGs on the BTFR. $V_\text{circ}$ is the circular velocity after correcting for pressure support (Eq. (2)). For star-dominated galaxies (McGaugh 2005) and gas-dominated ones (McGaugh 2012), $V_\text{circ}$ is measured along the flat part of the rotation curve. For TDGs, the shape of the rotation curve is uncertain, thus $V_\text{circ}$ may not correspond to the velocity along its flat part.
in MOND for \( n = 1 \) and \( n = 2 \), considering both the isolated case (\( V_{\text{ISO}} \) with \( g_{\text{NC}} = 0 \)) and the EFE (\( V_{\text{EFE}} \)). Formal errors are estimated considering the uncertainties on \( M_{\text{bar}} \) and allowing \( M_{\text{host}} \) to vary by a factor of 2. The MOND velocities are decreased by the EFE, but they are still systematically higher than the observed ones. For individual TDGs, the tension between MOND and observations is between \( \sim 1 \) and \( \sim 2\sigma \).

We stress that Eq. (4) grossly simplifies the EFE because it formally applies to the one-dimensional case and neglects the direction of the external field. We are also neglecting the time evolution of the EFE, which may be relevant here because TDGs start to form closer to the host galaxy (where the EFE is stronger) and are subsequently ejected to larger distances at high speeds. Since TDGs have long orbital timescales, they may respond in a non-adiabatic fashion to the rapidly varying EFE, keeping memory of the initial, stronger EFE. It would be interesting to investigate whether a more rigorous treatment of the EFE (using numerical simulations) could further decrease the velocities expected in MOND.

Finally, we note that MOND can also be interpreted as modified inertia (Milgrom 1994, 2006). In this case, the theory becomes strongly non-local and the force acting on a test particle depends on the full orbital history. A simple solution can be obtained in the case of stable, stationary, circular orbits (Milgrom 1994), but it is unclear what to expect for discs that have undergone less than one rotation. In this respect, TDGs greatly differ from typical disc galaxies and could, in principle, provide a test for such non-local theories.

### 7. Conclusions

We presented a systematic study of the gas dynamics in a sample of six TDGs around three interacting/merging systems: NGC 4694, NGC 5291, and NGC 7252 (“Atoms for Peace”). For NGC 4694 and NGC 5291, we re-analysed existing H I datacubes from D07 and B07, respectively. For NGC 7252, we presented new H I observations from the Jansky VLA, IFU A113, page 18 of 25.

Table 9. MOND analysis assuming dynamical equilibrium.

<table>
<thead>
<tr>
<th>Object</th>
<th>( D_b ) (kpc)</th>
<th>( g_{\text{NC}}/g_0 )</th>
<th>( g_{\text{E}}/g_0 )</th>
<th>( V_{\text{ISO}(1)} ) (km s(^{-1}))</th>
<th>( V_{\text{ISO}(2)} ) (km s(^{-1}))</th>
<th>( V_{\text{EFE}(1)} ) (km s(^{-1}))</th>
<th>( V_{\text{EFE}(2)} ) (km s(^{-1}))</th>
<th>( V_{\text{NC}} ) (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 5291N</td>
<td>65</td>
<td>0.021</td>
<td>0.073</td>
<td>77 ± 2</td>
<td>73 ± 2</td>
<td>62 ± 7</td>
<td>57 ± 7</td>
<td>45 ± 9</td>
</tr>
<tr>
<td>NGC 5291S</td>
<td>60</td>
<td>0.025</td>
<td>0.033</td>
<td>76 ± 3</td>
<td>73 ± 2</td>
<td>54 ± 8</td>
<td>49 ± 8</td>
<td>35 ± 6</td>
</tr>
<tr>
<td>NGC 5291SW</td>
<td>75</td>
<td>0.016</td>
<td>0.033</td>
<td>62 ± 3</td>
<td>59 ± 3</td>
<td>46 ± 7</td>
<td>43 ± 7</td>
<td>28 ± 7</td>
</tr>
<tr>
<td>NGC 7252E</td>
<td>50</td>
<td>0.044</td>
<td>0.019</td>
<td>52 ± 2</td>
<td>50 ± 2</td>
<td>30 ± 5</td>
<td>28 ± 5</td>
<td>18 ± 5</td>
</tr>
<tr>
<td>NGC 7252NW</td>
<td>80</td>
<td>0.017</td>
<td>0.015</td>
<td>63 ± 2</td>
<td>61 ± 2</td>
<td>41 ± 6</td>
<td>39 ± 6</td>
<td>21 ± 6</td>
</tr>
<tr>
<td>VCC 2062</td>
<td>20</td>
<td>0.024</td>
<td>0.022</td>
<td>41 ± 2</td>
<td>39 ± 2</td>
<td>27 ± 5</td>
<td>25 ± 5</td>
<td>16 ± 7</td>
</tr>
</tbody>
</table>

Notes. \( D_b \) is the projected distance of the TDG to the central galaxy remnant, which is used to estimate \( g_{\text{NC}} \).

1. The putative TDGs near NGC 7252 have near solar metallicities (\( 12 + \log(O/H) = 8.6 \)), indicating that they are currently forming out of pre-enriched tidal material. Moreover, they are associated with steep H I velocity gradients that represent kinematic discontinuities along the tails, pointing to local potential wells. Similar results have been found for three TDG candidates near NGC 5291 (B07) and one near NGC 4694 (D07). This confirms that the six galaxies in our sample are genuine TDGs.

2. The Hz kinematics of NGC 7252NW is complex and characterised by very broad line profiles. Most likely, we are observing H I regions dominated by turbulence and/or non-circular motions due to stellar feedback.

3. The H I emission associated with TDGs can be described by 3D disc models. These discs, however, have orbital times ranging from \( -1 \) to \( -3 \) Gyr, which are significantly longer than the TDG formation timescales (\( \lesssim 1 \) Gyr). This raises the question as to whether TDGs have had enough time to reach dynamical equilibrium. TDGs appear to be rotation-supported galaxies that are forming at \( z \sim 0 \) and, thus, are key objects to study the processes of disc building and relaxation.

If one assumes that TDGs are in dynamical equilibrium (as suggested by numerical simulations), the inferred dynamical masses are fully consistent with the observed baryonic masses. This implies that TDGs are devoid of DM, as predicted by theoretical models where tidal forces segregate baryons in the disc from DM in the halo. This also puts constraints on putative dark discs (either baryonic or non-baryonic) in the progenitor galaxies. Moreover, TDGs seem to systematically deviate from the baryonic Tully-Fisher relation. These results provide a challenging test for theories like MOND.

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Appendix A: Comparison with archival VLA data and single-dish observations for NGC 7252

For a sanity check, we retrieved from the VLA archive the H1 observations of NGC 7252 from Hibbard et al. (1994) and compare them with the new ones. We reduced the archival observations following standard procedures in AIPS and created a datacube with spatial resolution of 25″ (robust weights) and velocity resolution of 10.6 km s\(^{-1}\). The D-array data were interpolated to match the spectral resolution of the C-array data.

Figure A.1 shows a PV diagram obtained by collapsing the final datacube along the declination axis, giving a complete overview of the kinematic structure of the system. The comparison between the new (grayscale) and archival (red contour) data shows some differences on small spatial scales due to different noise levels in the two data sets. Overall the new VLA data are consistent with the archival ones.

From the new VLA data we derive a total H1 flux of 5.0 Jy km s\(^{-1}\). This is in good agreement with the single-dish measurement by Richter et al. (1994), who find a total H1 flux of 4.6 Jy km s\(^{-1}\) using the Green Bank Telescope (FWHM = 21′ × 21′). Other single-dish measurements (who rely on single pointings) reported lower fluxes: Huchtmeyer (1997) find 3.8 Jy km s\(^{-1}\) using the Effelsberg telescope (FWHM = 9′ × 9′), while Dupraz et al. (1990) find 3.6 Jy km s\(^{-1}\) using the Nançay telescope (FWHM = 4′ [E – W] × 22′ [N – S]). Most likely, the latter single-dish observations miss part of the H1 emission in the tidal tails, extending for ~12′ in the E-W direction. We conclude that no significant emission is missing from the new VLA data.

Appendix B: Comparison with B07 for NGC 5291

For the TDGs around NGC 5291, we find significantly lower values of \(M_{\text{dyn}}/M_{\text{rot}}\) than B07 because we estimate both higher values of \(M_{\text{gas}}\) (by factors of ~1.5 to ~2) and lower values of \(V_{\text{rot}}\) (by a factor of ~2). There are two reasons for the different estimates of \(M_{\text{gas}}\): (i) we integrate the H1 flux out to larger radii than B07, according to the results of our 3D disc models; this is the dominant effect; and (ii) we consider all the H1 emission that is consistent with a rotating disc, whereas B07 assumed that some H1 gas at the high/low velocity end was in the background/foreground (instead of being associated with the TDG potential well). The different estimates of \(V_{\text{rot}}\) are also driven by two separate reasons: (i) we find that line-of-sight velocities at the edges of the PV diagrams (employed by B07) tend to overestimate the “true” rotation velocity because they do not consider the line-broadening due to turbulent motions; and (ii) we find higher disc inclinations than assumed by B07. Hereafter, we discuss these two effects in details.

B07 derived rotation curves using the envelope-tracing method, which considers line-of-sight velocities near the edges of PV diagrams. Specifically, for a given radius along the major axis, they took the velocity towards the far edge of the PV diagram at 50% of the H1 peak level. For poorly resolved rotating discs, this is a rough way to consider beam-smearing effects, which are well-known to artificially broaden the emission-line profiles and systematically skew them towards the systemic velocity. The details of beam-smearing effects, however, depend on the intrinsic gas distribution, rotation curve shape, gas velocity dispersion, and disc inclination. Thus, full 3D models are required to take them into account (Swaters et al. 2009; Lelli et al. 2010). In particular, the velocity at 50% of the H1 peak may systematically overestimate the rotation velocity in discs with low values of \(V_{\text{rot}}/\sigma_{\text{H1}}\) (as dwarf galaxies), given that the broadening of the line profile is driven by both \(\sigma_{\text{H1}}\) and resolution effects. Our 3D disc models take all these observational effects into account and suggest that the rotation velocities of these TDGs are closer to the H1 peak than adopted by B07. This is demonstrated in Fig. B.1.

For the three TDGs near NGC 5291, we built additional 3D models following the same procedures of Sect. 5.1 and adopting the kinematic parameters of B07 (\(i = 45°\), \(\sigma_{\text{H1}} = 10\ \text{km}\ \text{s}^{-1}\) and \(V_{\text{rot}}\) from 50 to 70 km s\(^{-1}\) depending on the TDG). The right panels of Fig. B.1 compare PV diagrams along the major axis obtained from the observed cubes and these model cubes. The kinematic parameters from B07 produce PV diagrams that are too extended in the velocity direction. This leads to large negative residuals at high/low line-of-sight velocities and large positive residuals near the systemic velocity, indicating that \(V_{\text{rot}} \sin(i)\) is overestimated and \(\sigma_{\text{H1}}\) is underestimated. It is clear that our new kinematic parameters provide a much better description of the data (cf. with Figs. 5–7).

Regardless of the method employed to estimate the rotation velocities, these projected quantities must be corrected for inclination by multiplying by \(1/\sin(i)\). B07 assumed that the TDGs around NGC 5291 have the same inclination angle as the collisional H1 ring (\(i = 45°\)), which was estimated using numerical simulations. B07 pointed out that this value of \(i\) is uncertain because (i) the modelled ring is not exactly circular and its morphology depends on the details of the collision; and (ii) some simulated TDGs show a discrepancy between their rotation axis and the ring axis (up to 18° in a few cases). Using 3D disc models, we directly estimate \(i\) by comparing observed H1 maps with model H1 maps (before pixel-to-pixel renormalization). In left panels of Fig. B.1, the dashed ellipses correspond to disc models with \(i = 45°\). This value of \(i\) is roughly acceptable for NGC 5291N and NGC 5291SW, whereas it is clearly underestimated for NGC 5291S. The dashed ellipses in the top-middle
Fig. B.1. Disc models for NGC 5291N (top), NGC 5291S (middle), and NGC 5291SW (bottom) adopting the parameters from B07. Left panels: total H I maps from the observed cube (solid contours) and the model cube (dashed ellipse). The cross and dashed line illustrate the kinematical centre and major axis, respectively. The circle to the bottom-left corner shows the H I beam. Right panels: PV diagrams along the major axis obtained from the observed cube, model cube, and residual cube. Solid contours range from 2σ to 8σ in steps of 1σ. Dashed contours range from −2σ to −4σ in steps of −1σ. The horizontal and vertical lines correspond to the systemic velocity and dynamical centre, respectively.

Appendix C: Channel maps of individual TDGs

Figures C.1 and C.2 show H I channel maps from the observed cubes (red contours) and model cubes (blue contours). Contours are at −3σ (dashed), 3σ, 6σ, and 9σ. The channel maps are superimposed on an optical image of the TDG. The cross marks the kinematical centre. Line-of-sight velocities are indicated at the top-left corner. The H I beam is shown at the bottom-left corner. The model cubes are described in detail in Sect. 5.1. Here we provide a concise description for each TDG.

NGC 5291N is surrounded by H I emission belonging to the underlying tidal debris. At \( V_{\text{l.o.s.}} \approx 4145 \) to 4100 km s\(^{-1}\), there is extended H I emission to the west, which may correspond to another, more uncertain TDG candidate.

NGC 5291S is nicely reproduced by our disc model. At approaching velocities (\( V_{\text{l.o.s.}} \approx 4645 \) to 4635 km s\(^{-1}\)), there is some anomalous gas on the receding side of the disc.

NGC 5291SW is a complex case due to the low signal-to-noise ratio. The H I emission at \( V_{\text{l.o.s.}} \approx 4730 \) to 4720 km s\(^{-1}\) does not show a continuous, coherent kinematical structure, hence it has not been considered in the disc model.

NGC 7252E is well reproduced by our disc model despite it is a poorly resolved case with low signal-to-noise ratio. NGC 7252NW is closely reproduced by our disc model.

VCC 2062 is characterised by two distinct kinematic components, which overlap in both space and velocity (see PV diagrams in Fig. 10). The second, irregular component extends to the south-west at \( V_{\text{l.o.s.}} \approx 1155 \) to 1125 km s\(^{-1}\) and does not show a coherent velocity structure, hence it is not considered in our disc model.
Fig. C.1. H1 channel maps for NGC 5291N (top), NGC 5291S (middle), and NGC 5291SW (bottom). See Appendix C for a detailed description of this image.
Fig. C.2. H I channel maps for NGC 7252E (middle), and NGC 7252NW (bottom), and VCC 2062 (top). See Appendix C for a detailed description of this image.
Appendix D: Additional 3D disc models

Figures D.1 and D.2 compare 3D disc models based on a flat rotation curve (middle panel) and a solid-body rotation curve (right panel). The models are described in detail in Sect. 5.1.

The PV diagrams are obtained along the disc major axis. Solid contours range from $2\sigma$ to $8\sigma$ in steps of $1\sigma$. Dashed contours range from $-2\sigma$ to $-4\sigma$ in steps of $-1\sigma$. The horizontal and vertical lines correspond to the systemic velocity and dynamical centre, respectively.

**Fig. D.1.** Major axis PV diagrams for NGC 5291N (top), NGC 5291S (middle), and NGC 5291SW (bottom). See Appendix D for a detailed description of this image.
Fig. D.2. Major axis PV diagrams for NGC 7252E (top), NGC 7252NW (middle), and VCC 2062 (bottom). See Appendix D for a detailed description of this image.