Dynamics of Starbursting Dwarf Galaxies: I Zw 18.

Federico Lelli\textsuperscript{1}, Marc Verheijen\textsuperscript{1}, Filippo Fraternali\textsuperscript{1,2}, and Renzo Sancisi\textsuperscript{1,3}

\textsuperscript{1}Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV, Groningen, The Netherlands
e-mail: lelli@astro.rug.nl

\textsuperscript{2}Department of Astronomy, University of Bologna, via Ranzani 1, 40127, Bologna, Italy

\textsuperscript{3}INAF - Astronomical Observatory of Bologna, via Ranzani 1, 40127, Bologna, Italy

\textbf{ABSTRACT}

I Zw 18 is a prototype Blue Compact Dwarf (BCD), characterized by a strong starburst and extremely low metallicity ($Z \sim 0.02 Z_\odot$). It has long been considered a candidate young galaxy in the Local Universe, but recent studies indicate the presence of old stars. We analysed archival VLA observations of the 21 cm line and found that the H\textsubscript{I} associated to the starburst region forms a compact fast-rotating disk. The H\textsubscript{I} column densities are very high, up to $\sim$50-100 $M_\odot$ pc\textsuperscript{-2} ($\sim 0.6 - 1.2 \times 10^{22}$ atoms cm\textsuperscript{-2}). The rotation curve is flat with a steep rise in the inner parts, indicating the presence of a strongly central concentration of mass. Mass models with a dark matter halo show that baryons may dominate the gravitational potential in the inner regions. A radial inflow/outflow motion of $\sim$15 km s\textsuperscript{-1} is also present.

I Zw 18 appears structurally different from typical dwarf irregulars in terms of gas distribution, stellar distribution and dynamics. It may be considered as a “miniature” high-surface-brightness disk galaxy. These dynamical properties must be tightly related to the starburst. They also shed new light on the question of the descendants of BCDs. There is also extended H\textsubscript{I} emission towards the outlying stellar complex I Zw 18 C and a $\sim$13.5 kpc H\textsubscript{I} tail. An interaction/merger between gas-rich dwarfs is the most likely explanation for the starburst.


1. Introduction

Blue compact dwarfs (BCDs) are low-mass galaxies that are experiencing a starburst. They are usually characterized by small physical sizes ($\sim$ 2-3 kpc), low metallicities ($0.2 \lesssim Z/Z_\odot \lesssim 0.02$) and relatively large amounts of gas ($M_{\text{HI}}/L_\text{B} \gtrsim 1$). The question was raised whether they are young galaxies undergoing their first burst of star formation (Searle & Sargent 1972), but several studies based on surface brightness and color profiles (e.g. Gil de Paz & Madore 2005) as well as color-magnitude diagrams of resolved stellar populations (e.g. Tosi 2009) have demonstrated that BCDs contain also old stars, with ages $\gg 2-3$ Gyr. The star-formation histories of the nearby BCDs, as derived using color-magnitude diagrams (e.g. Tosi 2009), show that the starburst is a short-lived phenomenon, typically sustained for $\sim$100 Myr (e.g. McQuinn et al. 2010). Thus, BCDs are transition-type dwarfs, but it is not clear whether there are evolutionary connections with dwarf Irregulars (dIr), Spheroidals (dSphs) and/or Ellipticals (dEs) (e.g. Papaderos et al. 1996; van Zee et al. 2001). Also, the mechanisms that trigger, sustain and quench the starburst activity are not understood.

Regarding the H\textsubscript{I} distribution and kinematics, various studies (e.g. van Zee et al. 1998a, 2001) highlighted two striking properties of BCDs: i) they show strong concentrations of H\textsubscript{I} to the starburst region near the galaxy centre; ii) they usually have steep central velocity gradients. Both properties are not observed in more quiescent dIr (e.g. Swaters et al. 2002). This suggests a close connection between the starburst, the compact distribution of baryons (gas and stars) and the H\textsubscript{I} kinematics. The nature of the steep velocity gradients is not clear and two main interpretations are possible: i) fast rotation (e.g. van Zee et al. 2001), ii) gaseous inflows/outflows (e.g. Kobulnicky & Skillman 2008, Cannon et al. 2004). Fast rotation in the inner regions would indicate the presence of a strong concentration of mass, that may be either luminous or dark. Gaseous inflows/outflows would be linked to fuelling processes and/or feedback mechanisms.

On larger scales, BCDs usually show extended and diffuse H\textsubscript{I} structures that may form reservoirs for fueling the starburst. Generally, two different kinds of structures are observed: i) extended H\textsubscript{I} disks in regular rotation, e.g. NGC 2915 (Elson et al. 2010), NGC 2366 (Oh et al. 2008); ii) complex filamentary structures, e.g. II Zw 40 (van Zee et al. 1998a), NGC 5253 (Kobulnicky & Skillman 2008). The study of these extended H\textsubscript{I} structures can provide key information on the triggering mechanism (external vs internal processes), the properties of the progenitor galaxies (gas-rich dIr vs gas-poor dEs/dSphs), and the possible presence of massive gas inflows/outflows.

We present here a H\textsubscript{I} study of I Zw 18, the BCD prototype (e.g. Zwicky 1966; Searle & Sargent 1972). I Zw 18 is one of the most metal-poor galaxies known (12+log(O/H)$\sim$7.2, Izotov & Thuan 1999) and has long been considered a candidate young galaxy in the Local Universe, formed within the last 0.5 Gyr (e.g. Papaderos et al. 2002; Izotov & Thuan 2004). However, Aloisi et al. (2007), using HST observations, detected stars older than 1-2 Gyr and ruled out the possibility that I Zw 18 is a truly primordial galaxy (as also suggested by e.g. Aloisi et al. 1999, Oxlina & Mouchine 2005). The intense star-formation activity started only $\sim$20 Myr ago (e.g. Aloisi et al. 1999). Two key questions remain open: What triggered the starburst? Why is the metallicity so low?

Previous H\textsubscript{I} studies (Viallefond et al. 1987; van Zee et al. 1998b) showed that I Zw 18 is characterized by a strong central concentration of H\textsubscript{I} and a steep velocity gradient, as is typical
for BCDs. Also, the optical galaxy is surrounded by an extended H I envelope that was described by van Zee et al. (1998b) as "a fragmenting H I cloud in the early stages of galaxy evolution". We analysed archival H I data in order to: i) investigate the relation between the gas distribution and the starburst activity; ii) clarify the nature of the velocity gradient; iii) study the structure, kinematics and origin of the extended gas.

2. Data reduction & analysis

We analysed public H I data taken from the VLA archive. The observations were carried out between 1993 and 2004, using the VLA in all 4 configurations (see table 1). Data from the B, C, and D configurations were presented by van Zee et al. (1998b). In this new analysis, we included also data taken in 2004 with the high-resolution A-array configuration. The correlator was used in 2AD mode, with a total bandwidth of 0.8 MHz ($\sim$165 km s$^{-1}$). An on-line Hanning taper was applied to the data, producing 127 spectral line channels with a width of 6.3 kHz ($\sim$1.3 km s$^{-1}$).

The raw UV data were interactively flagged, calibrated and combined using the AIPS package and following standard VLA procedures. Next, the UV data were mapped using a robust weighting technique (Briggs 1995) and various Gaussian baseline tapers to attenuate the longest baselines. We built three datacubes with different spatial resolutions and pixel sizes by using different combinations of the Robust parameter and the taper FWHM (see table 2). After various trials, we chose the combinations that minimize sidelobes and wings in the beam profiles.

After the Fourier transform, the datacubes were analysed using the Groningen Imaging Processing SYstem (GIPSY) (van der Hulst et al. 1992). Continuum maps were constructed by averaging line-free channels. Because of the small bandwidth of the observations, few line-free channels were available and the resulting continuum-subtracted datacubes showed correlated noise in the spectral direction. Thus, we constructed a continuum map by using a mask, defining the area of H I emission in every channel and averaging, for each spatial pixel, all the channels without H I signal. The masks were constructed by smoothing the datacubes both in velocity (by a factor 4) and spatially (by a factor ~3, i.e. at 45", 10" and 5" for the low, intermediate and high resolution data, respectively) and clipping at 2.5$\sigma$ (where $\sigma$ is the noise in the smoothed cubes). The masks were inspected channel by channel and remaining noise peaks were botted out.

The use of a mask for the continuum subtraction may have the disadvantage that the noise is no longer uniform across the channel maps, as a different number of channels is used at every pixel to build the continuum map. Thus, we built signal-to-noise (S/N) maps for every channel (similarly to Verheijen & Sancisi 2001) and calculated a pseudo-1$\sigma$ contour by averaging the values of the pixels with 0.75 < S/N < 1.25. The resulting pseudo-1$\sigma$ level is close to that obtained by calculating the noise in a box without signal, suggesting that the noise is still almost uniform.

The channel maps were cleaned (Högbom 1974) down to 0.5$\sigma$, using the masks to define the search areas for the clean-components, which were then restored with a Gaussian beam of the same FWHM as the antenna pattern. Next, to boost the S/N-ratio, the cubes were smoothed in velocity to a resolution of 5.2 km s$^{-1}$ ($\sim$10.4 km s$^{-1}$ for the high-resolution data) and spatially to 20", 5" and 2" for the low, intermediate and high resolution data, respectively. Table 2 summarizes the properties of the cubes. Total H I maps were constructed by summing the signal inside the clean-masks. A pseudo-3$\sigma$ contour was calculated following Verheijen & Sancisi (2001). Velocity fields were built by fitting a Gaussian function to the H I line profiles. Fitted Gaussians with a peak intensity less than 2.5$\sigma$ and a FWHM smaller than 5.2 km s$^{-1}$ were discarded; remaining noise in the velocity fields (i.e. signal outside the pseudo-3$\sigma$ contour of the total H I maps) was botted out. The H I line profiles are quite broad and asymmetric, thus the velocity fields must be considered just as a rough indication of the global kinematics. Our kinematical analysis is based on Position-Velocity diagrams (Sect. 3) and on 3D models of the observations (Sect. 4.1).

3. H I distribution and kinematics

In this section we describe the overall H I structure of I Zw 18. We adopt the standard nomenclature introduced by Davidson et al. (1989). The main body is designated as I Zw 18 A (Fig. 2, top-right) and is characterized by two starburst regions; one to the North-West (NW) and one to the South-East (SE). The light concentrations denoted by Davidson et al. (1989) with B, D and E are background galaxies. The stellar complex to the NW is named I Zw 18 C or C-component. We assume a distance of 18.2 Mpc, as derived from the tip of the red giant branch (Aloisi et al. 2007) and confirmed by observations of Cepheids (Fiorentino et al. 2010).

We use data at three different resolutions (see table 2) in order to probe different spatial scales and H I column densities.
Fig. 1: Channel maps at a resolution of 20″ (top) and 5″ (bottom). Red-solid contours are at 1.5, 3, 6, 12, 24 × σ. Red-dashed contours are at -3, -1.5 × σ. Black contours show two isophotes of a B-band image (from Gil de Paz et al. 2003); the object to the North-East (R.A. = 9h 30m 34s, DEC = 55° 28′′) is a foreground star.
Fig. 2: **Top**: integrated H\textsubscript{I} maps at a resolution of 20\arcsec (left) and 5\arcsec (right), overlayed on a HST image (from Aloisi et al. 2007). The box in the left panel shows the area covered by the right panel. The dashed line corresponds to the pseudo-1.5\textsigma density contour. In the map at 20\arcsec, contours are at 0.25 (dashed), 0.5, 1, 2, 4, 8, 16 \times 10^{20} \text{atoms cm}^{-2}. In the map at 5\arcsec, contours are at 3 (dashed), 6, 12, 24, 48 \times 10^{20} \text{atoms cm}^{-2}. The circle shows the beam size. **Middle**: velocity fields at a resolution of 20\arcsec (left) and 5\arcsec (right). The box in the left panel shows the area covered by the right panel. Contours range from 722.4 to 805.6 km s\textsuperscript{-1}, with steps of 5.2 km s\textsuperscript{-1}. The circle shows the beam size. The dashed line shows the path followed to obtain the position-velocity diagram. **Bottom**: position-velocity diagrams at a resolution of 20\arcsec (left) and 5\arcsec (right). Contours are at -1.5 (dashed), 1.5, 3, 6, 12, 24 \times \textsigma. The box in the left panel shows the region covered by the right panel. The vertical line corresponds to the cross in the velocity fields.
3.1. The low-resolution view

The low-resolution data (with FWHM = 20′′ ~ 1.8 kpc and 3σ column density sensitivity \(N_{\text{HI}}(3\sigma) \sim 4 \times 10^{15} \text{ atoms cm}^{-2} \text{ per channel}\) illustrate the large-scale overall structure of I Zw 18.

Figure 1 (top) shows the channel maps, overlayed with two isophotes of a B-band image (from Gil de Paz et al. 2003). The central H1 emission presents a velocity gradient at a position angle P.A. = 140°-150°. At velocities from ~750 to ~720 km s\(^{-1}\) extended emission appears also to the South.

Figure 2 (top-left) shows the integrated H1 map, overlayed on a V-band HST image (from Aloisi et al. 2007). I Zw 18 A is associated with a strong concentration of gas, while diffuse emission extends beyond the optical galaxy, covering an angular size of ~3.5′ (~18.5 kpc). The H1 gas to the South of I Zw 18 A displays a tail-like morphology that extends over ~2.5′ (~13.5 kpc).

Figure 2 (middle-left) shows the velocity field. The main body (I Zw 18 A) is associated with the central velocity gradient. The southern “tail” does not seem to be kinematically connected with the SE region of I Zw 18 A, as the gas velocity changes abruptly from ~790 km s\(^{-1}\) to ~720 km s\(^{-1}\). Moreover, at the junction between I Zw 18 A and the “tail”, the H1 line profiles are double peaked, suggesting that there are two distinct components, possibly well-separated in space but projected to the same location on the sky.

Figure 2 (bottom-left) shows a Position-Velocity (PV) diagram, obtained from the 20′′ datacube following the “tail” (the dashed line overlayed on the velocity field). The central velocity gradient (associated with I Zw 18 A) is very steep and there is a spatial broadening towards the NW direction between ~700 and ~780 km s\(^{-1}\). The gas to the South forms a coherent kinematical structure at velocities between ~710 and ~760 km s\(^{-1}\). Strikingly, the broadened part of the PV-diagram and the “tail” are almost at the same velocities, suggesting that they may be physically connected. This hypothesis will be investigated further in Sect. 5.

3.2. The intermediate-resolution view

The intermediate-resolution data (FWHM = 5′′ ~ 440 pc and \(N_{\text{HI}}(3\sigma) \sim 4 \times 10^{19} \text{ atoms cm}^{-2} \text{ per channel}\) illustrate the H1 emission associated with I Zw 18 A and I Zw 18 C, and their possible connections.

Figure 1 (bottom) shows the channel maps, overlayed with two isophotes of a B-band image. The H1 emission to the NW is spatially resolved but still visible, whereas the southern “tail” is completely resolved out, indicating the diffuse nature of this gas. Between ~770 and ~740 km s\(^{-1}\) there are H1 clumps near the C-component. Their association with I Zw 18 C is very likely, because the H1 clumps are at the same velocities as the Hα emission (\(V_{\text{sys, Hα}}[C] = 751 \pm 5 \text{ km s}^{-1}\), Dufour et al. 1996).

Figure 2 (top-right) shows the integrated H1 map, overlayed on a V-band HST image. The main body is characterized by two H1 peaks, roughly corresponding to the NW and SE starburst regions. With respect to I Zw 18 A, the H1 is more extended to the North-West, in the direction of I Zw 18 C.

Figure 2 (middle-right) shows the velocity field, while figure 2 (bottom-right) shows a PV-diagram obtained following the dashed line on the velocity field. The steep velocity gradient is approximately along the two H1 peaks. The H1 emission to the NW shows a shallow velocity gradient from I Zw 18 A to I Zw 18 C and seems to connect the two stellar bodies. The presence of a “gaseous bridge” is supported also by Hα observations: Dufour & Hester (1990) detected diffuse Hα emission connecting I Zw 18 A and I Zw 18 C, while Dufour et al. (1996) measured Hα velocities between the two bodies that are very similar to those observed in H1 (their Fig. 3). Along I Zw 18 A, instead, the Hα velocity gradient shows a “wiggly” behaviour that is not observed in H1. This may be due to the presence of an Hα superbubble (see Martin 1996 and Sect. 5.2). Also, there is H1 emission to the West of the main body, that shows a velocity gradient and seems to have an Hα counterpart (see Sect. 5.2).

3.3. The high-resolution view

The high-resolution data (FWHM = 2′′ ~ 180 pc and \(N_{\text{HI}}(3\sigma) \sim 2 \times 10^{20} \text{ atoms cm}^{-2} \text{ per channel}\) show in detail the H1 emission associated to the NW and SE starburst regions.

Figure 3 shows the total H1 map in grayscale (left) and in contours overlayed on a Hα image (middle). The two H1 peaks are spatially resolved. The H1 clump to the SE coincides with a complex of H2 regions and has a strong peak, where the H1...
column density reaches $\sim 100 \, M_\odot \, \text{pc}^{-2} \, (\sim 1.2 \times 10^{22} \, \text{atoms cm}^{-2})$. In between the two clumps, an H I hole is associated with a strong H II region, suggesting that the neutral gas has been consumed, ionized and/or blown out by young stars. The H I clump to the NW coincides with a H$\alpha$ shell, that surrounds the bulk of the young stars (see Fig. 1 of Cannon et al. 2002). This shell is probably connected with the high-velocity H$\alpha$ emission detected by Dufour et al. (1996) and Martin (1996) at $\pm 200 \, \text{km s}^{-1}$ with respect to the systemic velocity.

The velocity field at 2$''$ resolution is shown in Fig. 3 (right). This velocity field is very uncertain because of the clumpy H I distribution, the asymmetric line profiles and the low S/N-ratio of the data at this high angular resolution. However, it shows a clear velocity gradient from the SE to the NW region, as already observed at lower resolutions. The H I depression is in the approaching NW side of the galaxy.

4. Dynamics of I Zw 18 A

In Sect. 3 we described the overall structure of I Zw 18. Two main facts need to be explained: i) the nature of the steep velocity gradient associated with I Zw 18 A; ii) the origin of the extended H I emission to the South and to the North-West of the galaxy. In this section we will focus on the dynamics of I Zw 18 A, while in Sect. 5 we will study the large-scale gas emission.

4.1. Kinematical models

There is some controversy in the literature regarding the velocity gradient of I Zw 18 A: Viallefond et al. (1987), Petrosian et al. (1997) and van Zee et al. (1998b) analysed 2D velocity fields and interpreted the gradient as rotation, whereas Skillman & Kennicutt (1993) and Dufour et al. (1996) obtained 1D long-slit spectroscopy and argued that the gradient may result from the merger of two (or more) gaseous clouds. The velocity gradient is along the optical major axis of the galaxy (Fig. 4) and the velocity field shows the typical pattern due to rotation: this strongly suggests the presence of a rotating disk. Here we present 3D kinematical models, which demonstrate that the H I disk is differentially rotating and has a global inflow/outflow motion.

The disk is modelled by a set of gas rings, with fixed centre, systemic velocity, position angle, inclination, surface density, thickness, velocity dispersion and rotation velocity. The centre, the systemic velocity and the position angle were estimated by eye using both optical and H I data (see table 3). The centre is between the NW and the SE starburst regions (see Fig. 4, right). For the radial distribution, we used the H I surface density profile, derived from the total H I map at 2$''$ resolution by azimuthally averaging over ellipses (Fig. 6, top). For the vertical distribution, we assumed an exponential law $\exp(-z/z_0)$. We built a set of models with different values for the inclination $i$, the scale height $z_0$ and the velocity dispersion $\sigma_{HI}$, assuming that each of these parameters is constant with radius. The inclination and the scale height are constrained by the observed H I map; their values are slightly degenerated but do not strongly affect the final result; we assumed $i = 70^\circ$ and $z_0 = 100 \, \text{pc}$ (see Fig. 4, right). The mean velocity dispersion is constrained by the shape of different PV-diagrams and values higher than $\sim 10 \, \text{km s}^{-1}$ are ruled out; we assumed $\sigma_{HI} = 7.5 \, \text{km s}^{-1}$. A thickness of 100 pc and a H I velocity dispersion of 7.5 km s$^{-1}$ are typical values for a H I disk.

The actual H I distribution of I Zw 18 A is clearly not axisymmetric (see Fig. 3). Thus, once the structural and geometrical parameters of the disk were fixed, we built models with axisymmetric kinematics but a clumpy H I distribution, i.e. the surface density varies with position as in the observed H I map. The procedure is as follows: we built a disk model with uniform density distribution (fixing $z_0$, $\sigma_{HI}$ and the rotation curve), projected it on the sky and then renormalized the H I line profiles at every spatial position in order to reproduce the H I density distribution observed at 2$''$ resolution. For the rotation curve, we tried
Fig. 5: Comparison between different 3D kinematical models and the observations. **Top**: Position-Velocity diagrams at a resolution of 2″ and 5″. The slice position are the major and minor axis, as indicated in Fig. 4 (left). Contours are at -1.5 (dashed), 1.5, 3, 6, 12 \times \sigma. **Bottom**: Channels maps at 2″ resolution (red contours) overlayed with two models: differential rotation (black-solid contours) and solid body rotation (black-dashed contours). Contours are at 2\sigma. The cross marks the galaxy centre. The circle shows the beam size. See text for details.
Table 3: Properties of I Zw 18.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>I Zw 18 A</th>
<th>I Zw 18 C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (B1950)</td>
<td>09°30'30.3'' ± 0.1</td>
<td>09°30'27.9'' ± 0.2</td>
</tr>
<tr>
<td>$\delta$ (B1950)</td>
<td>55°27'47'' ± 1''</td>
<td>55°28'06'' ± 2''</td>
</tr>
<tr>
<td>$V_{vss}$ (km s$^{-1}$)</td>
<td>767 ± 4</td>
<td>751 ± 5</td>
</tr>
<tr>
<td>Position Angle (°)</td>
<td>145 ± 5</td>
<td>-</td>
</tr>
<tr>
<td>Inclination Angle (°)</td>
<td>70 ± 4</td>
<td>-</td>
</tr>
<tr>
<td>$V_{rot}$ (km s$^{-1}$)</td>
<td>38 ± 4.4</td>
<td>-</td>
</tr>
<tr>
<td>$L_B$ ($10^7 L_\odot$)</td>
<td>13.9</td>
<td>1.1</td>
</tr>
<tr>
<td>$L_R$ ($10^7 L_\odot$)</td>
<td>5.8</td>
<td>0.4</td>
</tr>
<tr>
<td>$M_{HI}$ ($10^8 M_\odot$)</td>
<td>1.0</td>
<td>≤1.2</td>
</tr>
<tr>
<td>$M_{dust}$ ($10^8 M_\odot$)</td>
<td>3 ± 1</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes. Optical luminosities were calculated using the apparent magnitudes from Papaderos et al. (2002), the distance from Aloisi et al. (2007) and the solar absolute magnitudes from Binney & Merrifield (1998).

The H1 mass of I Zw 18 C refers to the extended emission described in Sect. 5, although only part of this gas may be physically associated with the C-component. The southern “tail” accounts for ~ 0.5 x $10^8 M_\odot$.

two extreme cases: solid body (slowly rising rotation curve) and differential (steeply rising and flat rotation curve).

Figure 5 (top) shows PV-diagrams obtained from different models and from the observations at a resolution of 2'' and 5''. The slice positions are the major and minor axis, as indicated in Fig. 4 (left). The velocity gradient along the major axis is grossly reproduced by all the models. This demonstrates that: i) a rotating disk is a good representation of the data; ii) the asymmetry between the NW and the SE region is mostly caused by the clumpy H1 distribution. Moreover, it is possible to discriminate between solid body and differential rotation. The observed PVD along the major axis shows H1 emission close to the galaxy centre ($R < 5''$) at high rotational velocities (~810 and ~730 km s$^{-1}$). The solid body model does not reproduce such emission, as the gas in the inner radii is mostly concentrated near the systemic velocity. The differentially rotating model, instead, correctly reproduces the high-velocity gas. This is clearly illustrated by the channel maps at 2'' resolution at receding velocities (Fig. 5, bottom): the solid body model (dashed line) is not extended enough towards the galaxy centre, whereas the differentially rotating model (solid line) gives a good match with the observations. The approaching NW side of the galaxy is not reproduced as well as the receding SE side. The NW starburst region is more active than the SE one (Contreras Ramos et al. 2011) and this may affect its local kinematics. Nonetheless, also on this side, a differentially rotating disk is preferable to a solid body one.

A simple rotating disk (independently from the assumed rotation curve) cannot reproduce the observed PV-diagrams along the minor axis (Fig. 5, top), because of the kinematic asymmetry and the presence of H1 emission at velocities forbidden by circular motions. This effect is visible also in the velocity field at 5'' resolution (Fig. 4, left): the kinematic minor axis, defined by the contours close to the systemic velocity, is not orthogonal to the kinematic major axis. Usually, this is attributed to radial motions (e.g. Fraternali et al. 2002). Alternatively, the non-orthogonality between the minor and major axes may indicate the presence of a bar-like or oval distortion (e.g. Bosma 1978). The optical images of I Zw 18, however, do not indicate the presence of such strong distortions. We improved the differentially rotating model by adding a global radial motion of 15 km s$^{-1}$. The resulting model reproduces the H1 emission at forbidden velocities. The model, however, cannot reproduce all the details present in the observed PV-diagram. The non-circular motions are not uniform across the disk and small variations (of the order of 3-4 km s$^{-1}$) could account for the observed discrepancies. It is not possible to discriminate between inflow and outflow, as it is not known which side of the disk is the near one. Vertical motions with roughly the same speed as the radial ones may also be present. Non-circular motions in excess of 20 km s$^{-1}$ are ruled out, confirming that the disk kinematics is dominated by rotation.

The rotation curve used to build the best model was not derived from a standard tilted-ring fit of the velocity field (Begeman 1987), but it was derived with a trial and error approach building a series of 3D models. The uncertainties on the rotation velocities are difficult to quantify. We made a conservative estimate of the uncertainties assigning an error equal to $\Delta V/2.35 = 4.4$ km s$^{-1}$, where $\Delta V$ is the velocity resolution of the 2'' datacube. The first point of the rotation curve is the most uncertain, as the velocity dispersion in the inner ring may be higher than the mean value of 7.5 km s$^{-1}$. For example, if $\sigma_{HI}$ is assumed to be 10 km s$^{-1}$ higher than the mean value, the rotation velocity would decrease of $\sim$5 km s$^{-1}$. We calculated the asymmetric drift correction following Meurer et al. (1996), but it turns out to be smaller than the errors.

4.2. Mass models

In Sect. 4.1 we showed that I Zw 18 A has a rotating H1 disk. The rotation curve is uncertain, but it shows an inner steep rise and an outer flat part. This indicates the presence of a strong central concentration of mass, that may be luminous or dark. Using this rotation curve, we built mass models to estimate the relative contributions of luminous and dark matter to the gravitational potential. We followed Begeman (1987).

The contribution of the gaseous disk was computed using the surface density profile derived from the total HI map at 2'' resolution (Fig. 6, top), multiplied by a factor 1.4 to take into account the presence of Helium. The possible gravitational effect of the H1 components outside the disk (i.e. the “tail” to the South and the extensions to the North-West and to the West) was not taken into account. Molecular gas was not explicitly considered in the mass model because its amount is very uncertain (Leroy et al. 2007). However, if molecules are distributed as the stars, their contribution is reflected in an increase of the stellar mass-to-light ratio ($M_*/L_\odot$). Consistently with the models in Sect. 4.1, we assumed an exponential vertical distribution with $z_0 = 100$ pc.

The contribution of the stars was computed using the R-band surface brightness profile from Papaderos et al. (2002) (Fig. 6, middle), that is derived from an HST image after the subtraction of the nebular emission (dominated by the Hr line). The color profiles from Papaderos et al. (2002) (their Fig. 11) show that, after the subtraction of the nebular emission, the color of I Zw 18 A is almost constant with radius. Thus, it makes sense to use a constant value of $M_*/L_\odot$. We assumed a stellar disk with a vertical density distribution given by $\rho(z) = \text{sech}^2(z/z_0)$ (van der Kruit & Searle 1981), with $z_0 = 100$ pc.

For the dark matter distribution, we assumed a pseudo-isothermal halo described by equation:

$$\rho_{DM}(r) = \frac{\rho_0}{1 + (r/r_c)^2},$$

(1)

where $\rho_0$ is the central density and $r_c$ is the core radius. $\rho_0$ and $r_c$ are free parameters of the mass models.

Figure 6 (bottom) shows the “maximum disk” decomposition of the rotation curve. The resulting stellar mass-to-light ratio is $M_*/L_\odot \sim 1.5$. In the maximum disk hypothesis, the baryons dominate the gravitational potential in the inner regions, while
the dark matter halo dominates in the outer parts. The parameters of the halo are uncertain because the sampling of the rotation curve is poor. The halo shown in Fig. 6 (bottom) has: \( \rho_0 = 833 \times 10^{-2} \, \text{M}_\odot \, \text{pc}^{-3} \) and \( r_e = 0.13 \, \text{kpc} \).

A \( M_*/L_R \sim 1.5 \) implies a stellar mass of \( \sim 9 \times 10^7 \, \text{M}_\odot \). According to Aloisi et al. (1999), the starburst started \( \sim 20 \, \text{Myr} \) ago with a star-formation rate (SFR) of \( 6 \times 10^{-2} \, \text{M}_\odot \, \text{yr}^{-1} \), giving a mass in young stars of \( \sim 10^6 \, \text{M}_\odot \). Thus, the newly formed stars and the concentration of H I cannot explain the steep rise of the rotation curve, implying that the mass concentration is due to either old stars, or molecules, or dark matter. Old stars have been detected (Aloisi et al. 2007) and their total mass can be constrained by deriving the galaxy Star-Formation History from Color-Magnitude diagrams. The maximum-disk value requires a mean SFR of \( \sim 7 \times 10^{-3} \, \text{M}_\odot \, \text{yr}^{-1} \) over the last 13 Gyr, that cannot be ruled out. Regarding molecules, the upper limit for the H_2 mass within \( \sim 400 \, \text{pc} \) is \( \sim 7 \times 10^7 \, \text{M}_\odot \) (Leroy et al. 2007), using a Galactic CO-to-H_2 conversion factor (X_{CO}). However, Leroy et al. (2007) argued that, in I Zw 18, X_{CO} may be \( 10^{-2} \) times the Galactic value. The same result is found by extrapolating the relation between X_{CO} and metallicity by Boselli et al. (2002) down to the metallicity of I Zw 18. Thus, the H_2 mass within \( \sim 400 \, \text{pc} \) may be dynamically important and as high as \( \sim 7 \times 10^7 \, \text{M}_\odot \).

We also considered MOnod Newtonian Dynamics (MOND) (Milgrom 1983, Sanders & McGaugh 2002) to describe the rotation curve. We fixed \( a_0 = 1.21 \times 10^{-8} \, \text{cm} \, \text{s}^{-2} \) (Begeman et al. 1991) and the distance \( D = 18.2 \, \text{Mpc} \) (Aloisi et al. 2007), thus the only free parameter is \( M_*/L_R \). MOND provides acceptable fits and gives \( M_*/L_R = 1.5 \) using the “standard” interpolation function (Milgrom 1983) and \( M_*/L_R = 1 \) using the “simple” one (Famaey & Binney 2005).

Following McGaugh (2011), we check the position of I Zw 18 A on the baryonic Tully-Fisher relation. The galaxy follows the correlation within the observed scatter.

5. The extended emission

In this section we study the extended H I emission. This may provide some clues to the mechanism that triggered the starburst. Also, we compare the large-scale H I and H_α emission to investigate the possible presence of outflows.
Fig. 8: The H I emission at 30″ resolution, after the subtraction of the main body. Left: B-band image overlayed with the total H I map. Countours are at 2.4, 4.8, 9.6, 19.2 \times 10^{19} \text{atoms cm}^{-2}. Middle: Velocity field. Contours range from 735.8 to 767 km s\(^{-1}\) with steps of 10.4 km s\(^{-1}\). The cross shows the position of I Zw 18 A. The dashed line shows the path followed to obtain the position-velocity diagram. Right: Position-Velocity diagram. Countours are at -1.5 (dashed), 1.5, 3, 6, 12 \sigma, where \(\sigma = 0.3 \text{ mJy/beam}\). The vertical line corresponds to the cross in the velocity field. The star shows the H\(\alpha\) velocity and the spatial position of I Zw 18 C.

5.1. The C-component and the H I tail

In Sect. 3.1 we reported two puzzling results (see Fig. 2, left): i) an H I “tail” at velocities between 710-760 km s\(^{-1}\) extending to the South of I Zw 18 A and kinematically disconnected from the South-East side of the central rotating disk; ii) a broadening of the H I emission in the PV-diagram almost at the same velocities (700-780 km s\(^{-1}\)) to the North-West (in the direction of I Zw 18 C). This is clearly shown in Fig. 7, where PV-diagrams at 20″ and 5″ resolution (with different column density sensitivities) are plotted on the same scale.

In order to study these components and their possible connection in more detail, we subtracted the compact H I disk of I Zw 18 A from the surrounding extended H I emission. We used the high-resolution data to define the emission from the disk and we subtracted this emission from the low-resolution datacube. Subsequently, we smoothed the residual datacube to 30″ and to 10.4 km s\(^{-1}\) and used it to obtain: i) a total H I map by summing the channels in the velocity range \(\sim\)700-780 km s\(^{-1}\); ii) a velocity field by estimating an intensity-weighted mean velocity; iii) a PV-diagram by following the tail (dashed line in Fig. 8).

Figure 8 shows the results of the subtraction. Interestingly, extended H I emission is centered on I Zw 18 C (left panel) and forms a coherent kinematical structure with velocities between \(\sim\)700 and 800 km s\(^{-1}\) (right panel). The physical association of the C-component with this surrounding H I emission is likely because the H\(\alpha\) systemic velocity of I Zw 18 C is \(\sim\)751±5 km s\(^{-1}\) (Dufour et al. 1996), (see star in Fig. 8, right).

The southern H I tail seems to be connected in space and in velocity with the H I structure around I Zw 18 C, as is shown by the velocity field (Fig. 8, middle). The connection may be behind or in front of I Zw 18 A. Possible interpretations of the extended H I emission will be discussed in Sect. 6.1.

5.2. The connection between H I and H\(\alpha\) emission

In Sect. 3.3 we pointed out the relative H I and H\(\alpha\) distributions in the inner regions of I Zw 18 A. Here we compare the distribution and kinematics of neutral and ionized gas on larger scales.

Figure 9 shows an H\(\alpha\) image (from Gil de Paz et al. 2003) overlayed with the H I emission. White contours show the H I emission at 2.″8 \times 3.″3 resolution, integrated in the velocity range 800-770 km s\(^{-1}\), and correspond to 5, 10, 20, 40 \times 10^{20} \text{atoms cm}^{-2}. The black line shows the pseudo-3\(\sigma\) contour of the total H I map at 5″ res.

Technically, we built a mask containing only the H I signal from the disk and we cleaned the datacube at 1.5″×1.4″ resolution down to 1\(\sigma\), using the mask to define the search areas. We restored the clean-components on a blank cube, using a Gaussian beam of 20″. The resulting “clean-components” cube contains only the emission from the disk, but at the desired resolution of 20″. Finally, the “clean-components” cube was subtracted channel by channel from the 20″ datacube.
the same velocities, suggesting that part of the diffuse H\textsc{i} may be associated with the outflow.

The H\textalpha\ emission presents also a prominent arc to the West of I Zw 18 A. This feature was first identified by Dufour & Hester (1990) and interpreted as a radiation-bound ionization front driven into the ISM. Petrosetal. (1997), instead, argued that the H\alpha\ arc contains also stellar emission and suggested that it is a structure with stars able to ionize the gas “in situ”. The H\textalpha\ to the West of I Zw 18 A is associated with the H\alpha\ arc. To show this, we summed the channel maps at $2.8 \times 3.3$ resolution in the velocity range 800-770 km s$^{-1}$ (see Fig. 9, white contours). Moreover, the H\alpha\ velocity field of Petrosetal. (1997) shows a gradient along the arc similar to the one observed in Fig. 2 (middle-right), confirming the physical association between H\alpha\ and H\alpha\.

The hypothesis of a radiation-bound ionization front is difficult to reconcile with the presence along the H\alpha\ arc of high-density ($\sim 10^{31}$ atoms cm$^{-2}$) neutral gas.

6. Discussion

6.1. Observational evidence & interpretation

This H\textalpha\ study of I Zw 18 has shown that:

- I Zw 18 A has a compact rotating disk with very high H\textalpha\ densities. The rotation curve is flat with a steep inner rise, indicating the presence of a strong concentration of mass. Also, a global inflow/outflow motion is present;
- I Zw 18 C is located in the direction of the major axis of I Zw 18 A and is almost at the same velocities as its approaching side. Gas emission with a smooth velocity gradient connects the two stellar bodies. I Zw 18 A appears to be at the centre of a diffuse H\textalpha\ structure;
- a H\textalpha\ tail extends to the South of I Zw 18 A out to $\sim 13.5$ kpc. The tail has a coherent kinematical structure and seems to be connected with the H\textalpha\ emission to the North-West.

Studies of the resolved stellar populations (Alolisi et al. 2007; Contreras Ramos et al. 2011) have shown that: i) the two starburst regions in I Zw 18 A (NW and SE) are embedded in a common envelope of old stars with ages $>1$ Gyr; ii) I Zw 18 A and I Zw 18 C are two completely separate stellar bodies and there are no stars between them; iii) also I Zw 18 C contains both old ($>1$ Gyr) and young ($\sim 10$ Myr) stars, but its current star formation rate (SFR) is lower than that of I Zw 18 A.

For the interpretation, we consider first the hypothesis of an interaction/merger of two (or more) gas-rich dwarfs. It is well-known that interactions/mergers can produce tidal tails (e.g. Toomre & Toomre 1972). Also, numerical simulations (e.g. Hibbard & Mihos 1995) suggest that mergers can lead to gas inflows, produce strong gas concentrations and trigger intense star formation. Thus, an interaction/merger may provide an explanation for: i) the concentration of H\textalpha, ii) the on-going starburst, and iii) the southern H\textalpha\ tail. I Zw 18 C may be either a “relic” of the interaction or a dwarf galaxy that is interacting/merging with I Zw 18 A. The two objects are at a projected distance of $\sim 2.2$ kpc, the difference between their systemic velocities is $\sim 12$ km s$^{-1}$, and they are connected by H\textalpha\ emission with a smooth velocity gradient. The ratio between the R-band luminosities of I Zw 18 A and I Zw 18 C is $\sim 14$, thus this would be classified as a minor merger. The merger hypothesis may also explain the extremely low metallicity, as discussed in the following.

Bekki (2008) argued that BCDs with low nebular metallicity are the results of mergers between gas-rich dwarfs with extended H\textalpha\ disks. According to his simulations, the central starburst is fuelled with metal-poor gas transferred from the outer regions of the extended disks, where the star formation and the chemical enrichment were not efficient due to the low H\textalpha\ densities. I Zw 18 is consistent with this picture, as the C-component is surrounded by an extended H\textalpha\ structure, that does not have a stellar counterpart and, likely, has not been efficiently enriched by SN explosions. Therefore, this H\textalpha\ structure may provide “fresh” unprocessed gas into the starburst regions of I Zw 18 A. A similar mechanism of metal dilution has been proposed also by Ektta & Chenzalur (2010) to explain why I Zw 18 and the other extremely metal-deficient BCDs are outliers of the mass-metallicity relation.

The presence of the extended H\textalpha\ emission, including the tail, has been considered above as supporting evidence for the merger, but could it be instead the result of a blowout from the starburst? Indeed, H\alpha\ observations of I Zw 18 suggest the presence of such an outflow (Sect. 5.2). Also, numerical simulations predict that starbursting dwarfs undergo massive outflows because they have a shallow gravitational potential (e.g. Mac Low & Ferrara 1999). The rate of the outflowing gas $dM_{\text{out}}/dt$ can be roughly estimated as:

$$\frac{dM_{\text{out}}}{dt} = 2 \times \epsilon \times S \times N R \times \frac{E_{\text{SN}}}{V_{\text{esc}}}$$ (2)

where $S/N R$ is the rate of supernovae (SN), $E_{\text{SN}}$ is the mean energy of a SN, $V_{\text{esc}}$ is the escape velocity and $\epsilon$ is the efficiency of the SN-feedback. Thus, $M_{\text{out}} = dM_{\text{out}}/dt \times \Delta T$, where $\Delta T$ is the duration of the starburst. Assuming $E_{\text{SN}} = 1.2 \times 10^{51}$ erg, $V_{\text{esc}} = \sqrt{2} \times V_{\text{rot}}, \epsilon = 0.15$, $\Delta T = 20$ Myr (Alolisi et al. 1999) and $S/N R = 0.01 \times S/FR$ with $S/FR = 0.06 M_\odot$ yr$^{-1}$ (Alolisi et al. 1999), we get $M_{\text{out}} = 5 \sim 8 \times 10^5 M_\odot$. The total mass of the extended gas is $\sim 1.6 \times 10^8 M_\odot$ (corrected for the presence of He). Thus, a massive outflow may explain all the diffuse gas if only slightly higher values of $S/FR$, $\Delta T$ and $\epsilon$ are assumed. Since the extended H\textalpha\ emission is entirely at approaching velocities, any outflow should be highly asymmetric and confined.

Finally, there is also the hypothesis of a “fragmenting H\textalpha\ cloud in the early stages of galaxy evolution”, which was suggested by van Zee et al. (1998b). This picture can explain the extremely low metallicity of I Zw 18, but is in contrast with the results of Alolisi et al. (2007), who concluded that I Zw 18 has old stars and is not a young galaxy in formation. Alternatively, I Zw 18 A and I Zw 18 C may be old stellar systems that are accreting cold gas from the inter-galactic medium and are now forming new stars. This may be in line with some simulations of dwarf galaxy formation (e.g. Kere\v{s} et al. 2005; Dekel & Birnboim 2006).

6.2. Comparison with other dwarf galaxies

The evolution of BCDs is still an open issue. In particular, it is not clear what objects can be identified as their progenitors and descendants (Papaderos et al. 1996; van Zee et al. 2001). It is useful, therefore, to compare their properties with those of other types of dwarf galaxies.

In Fig. 10 we compare I Zw 18 A with a typical dwarf irregular (UGC 7232), taken from the sample of Swaters et al. (2009). The H\textalpha\ observations for these two objects have almost the same linear resolution ($\sim 200$ pc), making it possible to compare H\textalpha\ surface densities and velocity gradients. The two galaxies have approximately the same H\textalpha\ size and the same rotation velocity at the last measured point, thus they have roughly the same dy-

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...Regarding other BCDs, it is known that their underlying stellar component, which is formed by old stars, is generally more compact than common dEs and dIrrs (e.g. Papaderos et al. 1996; Gil de Paz & Madore 2005). In particular, the old stellar component of the majority of BCDs has a typical central surface brightness $\mu_0 \sim 21$ mag arcsec$^{-2}$ in the B-band (e.g. Gil de Paz & Madore 2005), similar to high surface brightness (HSB) disk galaxies (e.g. van der Kruit & Freeman 2011). If the distribution of mass is strongly coupled to the distribution of light (Sancisi 2004), we expect that BCDs show a dynamical behaviour similar to that of HSB spiral galaxies, i.e. steeply rising rotation curves that can be described under the maximum disk hypothesis. This seems to be the case for I Zw 18 A. In all these respects, I Zw 18 A resembles a “miniature” HSB disk galaxy. There are already indications that BCDs may have “steeper rotation curves than similar luminosity, low surface brightness dwarf galaxies” (van Zee et al. 2001), but a detailed dynamical study is needed to trace reliable rotation curves and determine the relative contributions of gas, stars and dark matter to the gravitational potential.

7. Conclusions

We analysed H$\alpha$ observations of the blue compact dwarf galaxy I Zw 18 A. Our main results can be summarized as follows:

- the H$\alpha$ associated with the starburst region (I Zw 18 A) is in a compact rotating disk. The H$\alpha$ column densities are very high, up to $\sim$50-100 $M_\odot$ pc$^{-2}$ ($\sim 0.6-1.2 \times 10^{22}$ atoms cm$^{-2}$);
- the disk has a flat rotation curve with an inner steep rise. This indicates the presence of a strong concentration of mass, that may be luminous or dark. Baryons may dominate the gravitational potential in the inner regions;
- the disk has a radial inflow/outflow motion of $\sim$15 km s$^{-1}$;
- the stellar concentration to the North-West (I Zw 18 C) is surrounded by extended H$\alpha$ emission, smoothly connected with I Zw 18 A;
- a H$\alpha$ tail extends to the South of I Zw 18 A out to $\sim$13.5 kpc. It shows a coherent kinematical structure and seems to be connected with the H$\alpha$ emission to the North-West.

I Zw 18 A appears structurally different from a typical dIrr in terms of H$\alpha$ distribution, stellar distribution and dynamics. In particular, it has a strong central concentration of mass. It may be considered as “miniature” HSB disk galaxy. The H$\alpha$ concentration and the dynamical properties must be tightly linked with the starburst. They are also crucial to address the question of the progenitors/descendants of BCDs.

Regarding the mechanism that triggered the starburst, an interaction/merger between gas-rich dwarf galaxies seems to be the most likely hypothesis.

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References


Fig. 10: Comparison between I Zw 18 A (blue line) and a typical dwarf irregular UGC 7232 (red line), selected from the sample of Swaters et al. (2009). Top: H$\alpha$ surface density profile. Middle: R-band surface brightness profile. Bottom: H$\alpha$ rotation curve.