Chapter 8

Conclusions and future prospects

8.1 Summary and highlights

In this Ph.D. thesis, we investigated the structure, dynamics, and evolution of starbursting dwarf galaxies (hereafter blue compact dwarfs, BCDs). We considered 18 nearby objects that have been resolved into single stars by HST, providing their star-formation histories (SFHs) from the modelling of color-magnitude diagrams. For these 18 BCDs, we collected both new and archival 21 cm-line observations. By combining the HST information with H I observations, we could study in detail the possible relations between the starburst and the gas distribution and kinematics. To investigate the evolutionary links between BCDs and other types of low-mass galaxies, we compared the properties of these starbursting dwarfs with those of gas-rich irregulars (Irrs) and gas-poor spheroidals (Sphs). Here we summarize our main results, and discuss prospects for future research.

8.1.1 H I distribution and kinematics in BCDs

BCDs have, on average, higher central H I *densities and more complex* H I *kinematics than typical Irrs.*

The azimuthally-averaged H I surface density profiles of BCDs are different from those of other gas-rich galaxies. The BCDs in our sample have, on average, central H I surface densities a factor of ∼2 higher than typical Irrs (Chapter 4), in overall agreement with previous H I studies. Moreover, the H I distribution over the stellar body is clumpy, and the peak H I column densities can reach very high values, up to ∼50-100 $M_{\odot}$ pc^{-2} in I Zw 18 at a linear resolution of ∼200 pc (Chapter 2). The average extent of the H I disk with respect to the stellar body, instead, is similar for BCDs, Irrs, and gas-rich spirals ($R_{\rm H\,I}/R_{\rm opt} \simeq 1.7$).

Complex H I kinematics are more common in BCDs (∼50%) than in typical Irrs (∼10%); this may be related to stellar feedback and/or to the mechanism that triggered the starburst (interactions/mergers and/or disk instabilities). For 9 galaxies with a regularly-rotating H I disk, we derived rotation curves by building 3D disk models (Chapters 2, 3, and 4). The rotation curves of BCDs typically show a steep rise in the inner parts and a flat part in the outer regions. In 4 galaxies, we also found evidence for radial motions. We do not know the direction of these radial motions, but if we assume that they are an inflow, the inferred gas accretion rates would be ∼1 order of magnitude higher than the current star-formation rates (SFRs). Probably, these radial motions are recent and short-lived, given that their timescales are comparable to the orbital times and the burst durations.

8.1.2 Luminous and dark matter in BCDs

BCDs have both baryonic and gas fractions similar to typical Irrs, suggesting that the starburst does not eject a large fraction of gas out of the potential well.

For BCDs with accurate estimates of the rotation velocity, we calculated the dynamical mass $M_{\rm dyn}$ and the baryonic fraction $f_{\rm bar} = M_{\rm bar}/M_{\rm dyn}$ within the optical radius (Chapter 4). The baryonic mass $M_{\rm bar}$ was estimated using the stellar mass provided by the HST studies of the resolved stellar populations, which depends *only* on the assumed initial mass function (IMF) and on the gas-recycling efficiency. On average, BCDs have $f_{\rm bar} \simeq 0.3$ for a Kroupa IMF and $f_{\rm bar} \simeq 0.4$ for a Salpeter IMF. The average baryonic fraction may increase up to 0.5 if molecules are also taken into account, but one has to rely on indirect estimates of the molecular gas mass.

For 4 galaxies with a regularly-rotating H I disk centered on the stellar body, we decomposed the rotation curves into mass components. In particular, we broke the disk-halo degeneracy by using the stellar masses from the HST observations, under the assumption that the stellar mass-to-light ratio does not vary strongly with radius. We found that baryons (gas and stars) are generally not sufficient to explain the inner rise of the rotation curve, although they constitute $\sim$ 20 to 40% of the total mass within $\sim$2 disk scale-lengths.

Despite the starburst having injected $\sim$$10^{56}$ erg in the ISM during the past $\sim$500 Myr, BCDs have both baryonic and gas fractions similar to non-starbursting Irrs. This suggests that *either* BCDs do not expell a large amount of gas out of their potential well, *or* their gas fractions must have been much higher at the beginning of the burst. The former hypothesis seems more likely, given that we found no significant trend between the gas fractions and the starburst properties.

8.1.3 Starbursts and the evolution of dwarf galaxies

BCDs have a strong central concentration of dynamical mass (gas, stars, and dark matter) and likely evolve into "compact" Irrs and/or rotating Sphs; the starburst activity is closely related to the inner shape of the potential well.

BCDs have, on average, steeper rotation curves than typical Irrs (Chapters 2, 3, and 5), indicating that they have a high central dynamical mass density. In Chapter 5, we measured the inner circular-velocity gradient $d_R V(0)$ for 60 low-mass galaxies (including BCDs, Irrs, and rotating Sphs), using H I and/or stellar rotation curves from the literature. For gas-rich dwarfs, we found that $d_R V(0)$ correlates with the central surface brightness μ_0, the mean atomic gas surface density $\Sigma_{\rm gas}$ within the stellar body, and the SFR surface density $\Sigma_{\rm SFR}$. BCDs are in the upper parts of these relations, having high values of $d_R V(0)$. Similarly to spiral galaxies and massive starbursts, the star-formation activity in dwarfs can be parametrized as $\Sigma_{\rm SFR} = \epsilon \Sigma_{\rm gas}/\tau_{\rm orb}$, where $\tau_{\rm orb}$ is the orbital time on the solid-body portion of the rotation curve and ϵ ($\simeq 0.02$) is the fraction of atomic gas converted into stars during every orbit.

We identified several "compact" Irrs, that have values of $d_R V(0)$ similar to BCDs. These compact irregulars are candidate progenitors/descendants of BCDs. Rotating Sphs in the Virgo cluster follow the same correlation between

$d_R V(0)$ and μ_0 as gas-rich dwarfs. They have values of $d_R V(0)$ comparable to BCDs and compact Irrs, suggesting that evolutionary links between these types of dwarfs are possible. The evolutionary sequence BCD → compact Irr → rotating Sph is in overall agreement with the observational evidence, but an *external mechanism* is required to entirely remove the ISM from a compact Irr/BCD, such as ram-pressure stripping or galaxy harassment.

Toomre's criterion for large-scale gravitational instabilities provides a simple explanation for the correlation between $d_R V(0)$ and $\Sigma_{\rm gas}$. Moreover, if the progenitors of BCDs are compact Irrs, their steeply-rising rotation curves would imply high values of the critical surface-density threshold for gravitational instabilities, thus the gas could pile up in the center and reach high surface densities, eventually leading to a starburst. Alternatively, interactions/mergers between Irrs may lead to an overall contraction of their stellar and gaseous disks due to the loss of angular momentum, forming a central mass concentration and triggering the starburst.

8.1.4 Triggering the starburst in BCDs

BCDs have, on average, more asymmetric large-scale H I *distributions than typical Irrs, suggesting that an external mechanism triggered the starburst.*

The large-scale, diffuse H I emission in BCDs shows a broad variety of morphologies (Chapter 6). Several BCDs have heavily disturbed H I morphologies, characterized by strong asymmetries, long filaments, and severe offsets between the stellar and H I distributions, whereas other BCDs show only minor asymmetries. We quantified these asymmetries for both our sample of BCDs and a control-sample of typical Irrs. BCDs generally have more asymmetric H I morphologies than non-starbursting Irrs, indicating that some *external mechanism* triggered the starburst, such as interactions/mergers between gas-rich dwarfs or cold gas accretion from the IGM. Moreover, galaxies hosting an old burst ($\gtrsim$ 100 Myr) have more symmetric H I morphologies than galaxies hosting a young burst ($\lesssim$ 100 Myr), suggesting that the former ones had enough time to regularize their outer H I distributions since the epoch of the major interaction/accretion event.

We investigated the environment of the BCDs in our sample, and found that most of them have a potential perturber at a projected distance $\lesssim$ 200 kpc and with a similar systemic velocity (within ±300 km $\rm s^{-1}$). In several cases, however, the lack of accurate distances prevents us to exclude possible background/foreground objects. Three galaxies (I Zw 18, NGC 4449, and NGC 2366) are probably undergoing a minor merger with a smaller companion. Another three galaxies (NGC 1705, NGC 6789, and UGC 9128), instead, appear very isolated and have relatively-regular optical morphologies down to $\mu_{\rm R} \simeq 26$ mag $\rm arcsec^{-2}$. If these unperturbed stellar morphologies are confirmed by deeper optical images, these galaxies may represent cases of cold gas accretion in the nearby Universe, although the link to the central mass concentration would remain to be explained.

8.1.5 The coupling between baryonic and dynamical mass

For rotating galaxies, the central baryonic density closely relates to the central dynamical mass density.

For disk galaxies, a close relation exists between the distribution of light and the steepness of the inner rotation curve. We quantify this relation by measuring the inner circular-velocity gradient $d_R V(0)$ for 52 spiral and irregular galaxies with high-quality rotation curves. We found that $d_R V(0)$ correlates with the central surface brightness μ_0 over more than two orders of magnitude in $d_R V(0)$ and four orders of magnitude in μ_0. This is a scaling relation for disk galaxies that holds for objects of very different morphologies, luminosities, and sizes, ranging from dwarf irregulars to bulge-dominated spirals. The $d_R V(0) - \mu_0$ relation indicates that the central stellar density closely relates to the inner shape of the potential well, also for low-luminosity and low-surface-brightness galaxies that are expected to be dominated by dark matter.

8.2 Prospects for future research

8.2.1 Larger samples, better statistics

In this Ph.D. thesis, we studied 18 starbursting dwarf galaxies. The size of this sample allowed us to perform an in-depth study of the gas kinematics in each individual object and, at the same time, to draw general conclusions about starbursting dwarfs as a galaxy population. We remind, however, that accurate dynamical masses could be derived for 11 objects and rotation curves for 9 objects, while detailed mass models could be built for only 4 galaxies. Clearly, a detailed study of a larger sample of BCDs would provide better statistics and strengthen the results presented here. Moreover, when we compared the dynamical properties of gas-rich and gas-poor dwarfs, we considered only 8 Sphs, given that stellar rotation curves and R-band structural parameters were available in the literature for a limited number of objects. On-going and future studies of the stellar kinematics in Sphs will provide larger datasets, and allow us to make a more extensive comparison between the dynamical properties of gas-rich and gas-poor dwarfs. In particular, larger galaxy samples are needed to investigate whether the dynamical properties of BCDs, Irrs, and rotating Sphs show any dependence on the environment.

8.2.2 Star-formation histories of compact irregulars

The compact Irrs identified in Chapter 5 are candidate progenitors/descendants of BCDs. To further investigate their relation with starbursting dwarfs, it would be interesting to resolve them into single stars and derive their recent SFH. For the nearest objects ($D \lesssim 5$ Mpc), this can be achieved with HST observations, whereas for the most distant galaxies we should wait for next-generation facilities, such as the *European Extremely Large Telescope* (E-ELT). The compact Irr UGC 7232 (NGC 4190) has already been observed with HST by the ANGST project, but its recent SFH has not been studied in detail. Alternatively, one may attempt to constrain the recent SFH of compact Irrs by a detailed modelling of their spectral energy distribution (from far-UV to radio wavelengths) and/or by fitting stellar populations synthesis models to high-quality integrated spectra, although these techniques would provide recent SFHs that are less accurate than those from resolved stellar populations.

8.2.3 Searching for tidal features with deep photometry

The disturbed H I morphologies of BCDs suggest that some external mechanism triggered the starburst, such as interactions/mergers between gas-rich dwarfs or direct gas infall from the IGM. It would be useful to obtain very deep optical images for these objects (down to $\mu_{\mathrm{B}} \simeq 29 - 30$ mag arcsec^{-2}) to search for possible stellar tidal features and/or faint, low-surface-brightness companions. If these galaxies would still show *no* signs of tidal interactions at these low surface brightness levels, cold gas accretion would then be the most likely triggering mechanism.

8.2.4 The slope and scatter of the $d_R V(0) - \mu_0$ relation

The slope and the intrinsic scatter of the $d_R V(0) - \mu_0$ relation are not very well constrained. The situation can be improved in several ways:

1. In Chapter 7, we considered 52 galaxies with high-quality and high-resolution rotation curves from the literature. Clearly, more objects would improve our statistics and help to constrain the slope of the relation. In particular, only a few rotation curves were available for bulge-dominated galaxies. These objects lie in the top-right part of the relation and are crucial to constrain its slope. It would be helpful, therefore, to derive high-quality rotation curves for a large sample of bulge-dominated spirals and/or lenticulars, possibly using integral-field spectroscopy.

2. The errors on $d_R V(0)$ are generally dominated by distance uncertainties. More accurate distances (from Cepheids and/or the tip of the red giant branch) would substantially reduce the erros on $d_R V(0)$ and, possibly, the scatter along the relation. For the most distant objects, however, the Tully-Fisher relation would still be the only distance indicator available, thus improvements in its calibration are of great interest.

3. We estimated μ_0 from R-band observations. We made this choice because R-band surface brightness profiles were available from the literature for most of the galaxies. Surface brightness profiles in the K-band or at 3.6 μm would provide a better proxy for the central stellar density. This would improve our estimate of μ_0 and, possibly, reduce the scatter along the relation due to differences in dust attenuation and/or stellar populations.

In our opinion, the slope and the scatter of the $d_R V(0) - \mu_0$ relation provide crucial information on the link between baryonic and dynamical mass in the central parts of galaxies. Their exact values could put strong constrains on models of galaxy formation in a ΛCDM cosmology, as well as on alternative theories such as MOND. Future studies, therefore, should aim at improving our understanding of this relation, both from an observational and a theoretical perspective.