Starbursts, Dark Matter And Dwarf Galaxy Evolution

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Abstract. Optical and H\textsubscript{i} imaging of both dwarf irregular (dI) and Blue Compact Dwarf (BCD) galaxies reveal important clues on how dwarf galaxies evolve and their star formation is regulated. Both usually show evidence for stellar and gaseous disks. However, their total mass is dominated by dark matter. Gas rich dwarfs form with a range of disk structural properties. These have been arbitrarily separated them into two classes on the basis of central surface brightness. Dwarfs with $\mu_0(B) < 22$ mag arcsec$^{-2}$ are usually classified as BCDs, while those fainter than limit are usually classified as dIs. Both classes experience bursts of star formation, but with an absolute intensity correlated with the disk surface brightness. Even in BCDs the bursts typically represent only a modest $\sim 1$ mag enhancement to the $B$ luminosity of the disk. While starbursts are observed to power significant galactic winds, the fractional ISM loss remains modest. Dark matter halos play an important role in determining dwarf galaxy morphology by setting the equilibrium surface brightness of the disk.

1 Introduction

Despite their morphological differences dwarf irregular (dI), Blue Compact Dwarf (BCD), and dwarf elliptical (dE) galaxies have similar optical structures - their radial profiles are exponential, at least at large radii (e.g. [2,3,13]). Are there evolutionary connections between these morphologies? One scenario expounded by Davies & Phillips [4] starts with an initial dI galaxy; if its ISM manages to concentrate at the center of the galaxy a tremendous starburst occurs resulting in a BCD morphology. This starburst powers a galactic wind (e.g. [6,12]). If the wind is strong enough all of the ISM is expelled resulting in a dE morphology. If some ISM remains, the system fades back into a dI, and undergoes a few more dI $\Leftrightarrow$ BCD transitions before eventually expelling all of its ISM to become a dE. Here I will address the validity of this scenario. In Sec. 2, I compare the optical structure of dIs and BCDs; Sec. 3 details the H\textsubscript{i} structure and dynamics of two BCDs: NGC 1705 ($D = 6.2$ Mpc) and NGC 2915 ($D = 3.1$ Mpc), and compares them to dI galaxies; and Sec. 4 synthesizes the optical and radio results to form a new scenario where Dark Matter (DM) plays a dominant role in determining the morphology of gas rich dwarfs. Here I adopt $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. 
The optical structure and classification of gas rich dwarfs

The exponential profile portion of BCDs and dIs probably signifies the presence of a rotating disk, which are certainly typical of the gas distributions in these systems [24,4]. In addition to the disk component, BCDs usually have a blue high surface brightness excess of light in their centers, rich in H II emission and young star clusters [13,2]. I will call this blue excess the starburst, since it is responsible for the starburst characteristics of BCDs. The integrated colors of this component, after subtracting off the disk, indicate that it must be due to a young stellar population with an age $\sim 10$ Myr if instantaneous burst models are adopted or $\sim 100$ Myr if constant star formation rate models are adopted [14]. The strong H$\alpha$ fluxes are more consistent with the constant star formation rate models (because $\sim 10$ Myr old instantaneous bursts are no longer ionizing).

In either case this is much less than the Hubble time, confirming the starburst nature of this component. In comparison, the colors of the disk are typically like those of stellar populations forming continuously over a Hubble time (i.e. like dI galaxies, cf. [21]), or a bit redder suggesting an inactive population.

Surface brightness profile fitting provides a means to determine both the relative strength of the starburst, and the structural properties of the disk (see [14] for details). The outer portions of the profile are fitted with an exponential, yielding the extrapolated central surface brightness $\mu_0$, and scale length $\alpha^{-1}$ of the disk. The burst and disk are separated by assuming that the disk remains exponential all the way into the center. The strongest starbursts are about twice as bright as their hosts. Hence, while starbursts can outshine the host disk they are nevertheless modest $\lesssim 1$ mag enhancements to the total $B$ flux of BCDs. Typical flux enhancements are only a few tens of percent. About 20% of BCDs have exponential profiles all the way into their cores, hence they show no structural evidence for a starburst. The mass contribution of the starburst is even smaller than the flux contribution, typically $\lesssim 5\%$. These are not the $\sim 6$ mag starburst enhancements proposed to explain the excess of faint blue galaxies at moderate redshifts [1].

Figure 1 compares the disk parameters $\mu_0$, $\alpha^{-1}$ of both BCDs and dI galaxies. Note, $\mu_0$ does not include the contribution of the starburst core. While there is some overlap, we see that BCD distribution is offset from that of dIs particularly in $\mu_0$ which typically is 2.5 mag arcsec$^{-2}$ more intense in BCDs than in dIs. Structurally BCD disks are very different from those of dIs.

The absence of BCDs on the left half of Fig. 1 is puzzling. Does this mean that dI galaxies do not experience starbursts? Examination of surface brightness and color profiles [21] reveal several dIs with an exponential profile, and a higher surface brightness blue excess, structural evidence for starbursts in dIs. The episodic star-forming nature of dIs is well demonstrated using color-magnitude diagrams of the nearest ones (e.g. [8]). However the observed central surface brightness of the bursting dIs including the light of this central excess is typically $\mu(B) \gtrsim 22$ mag arcsec$^{-2}$, much fainter than the central regions of BCDs. While dIs do experience starbursts, they are pathetic and not usually recognized as
Fig. 1. (Left) Exponential disk parameters for samples of BCD and dI galaxies [14, 23, 20, 21].

Fig. 2. (Right) DM halo central density $\rho_0$ plotted against disk central surface brightness. Open squares are from de Blok & McGaugh [5], while diamonds represent NGC 1705 and NGC 2915. The top panel shows the results for maximum disk model fits, while the bottom panel shows Bottema disk fits. The circles on the right side of the top panel mark crude estimates of $\rho_0$ in 12 BCDs with published and unpublished RCs. The dotted line, at bottom, is a fit to the Bottema disk results with the relationship $\log(\rho_0) = 0.4 \log(\mu_0) + \text{Constant}$.

such since they are not intense enough. We see that there are both BCDs and dIs with central starbursts, as well as cases of both types that are exponential all the way into their centers. The separation into two classes appears to be an arbitrary segregation by central surface brightness of the underlying disk at $\mu_0(B) \approx 22$ mag arcsec$^{-2}$.

3 H I structure and dynamics of BCDs

Compared to dIs there are not that many H I imaging studies of BCDs; in part due to their small numbers and usual compact angular sizes. Two that have been well imaged in H I are NGC 2915 [16], and NGC 1705 [18].

Both galaxies show evidence of star formation churning up the neutral ISM. In NGC 2915, enhancements in the velocity dispersion correspond well to H$\alpha$ bubbles and peculiar star formation knots. However it does not appear that H I is being ejected from the system. In the center of the galaxy, where star formation is the most vigorous, $\sigma_{HI} \approx 40$ km s$^{-1}$ which is the same as the one dimensional velocity dispersion derived for the DM particles. Hence, star formation appears to be maintaining the central H I in virial equilibrium with the DM halo. This suggests that DM plays a role in the feedback process: if the starburst energizes
HI to have $\sigma_{HI}$ much larger than the halo velocity dispersion, then neutral ISM is thrown into the halo (or beyond) halting star formation.

NGC 1705 displays a strong galactic wind in Hα. There is a spur of HI emission obliquely jutting out from its HI disk that appears to be a neutral ISM extension of this wind. If so, then NGC 1705 has ejected about 8% of its neutral ISM at a mass loss rate at least comparable to the star formation rate. Nevertheless, even in this BCD with one of the most spectacular Hα outflows, the majority of the ISM is retained in a disk. This starburst is incapable of totally blowing away the ISM.

Although both galaxies have some kinematic irregularities their dominant structures are extended rotating disks which are strongly centrally peaked. These are typical properties of BCDs imaged in HI [22,24]. The disk of NGC 2915 is so extended that it has the HI appearance of a late type barred spiral. Similar galaxies include IC 10 [25] and NGC 4449 [1].

The rotation curves of both NGC 1705 and NGC 2915 show a fairly steep rise over the optical face of the galaxy which then becomes flat out to the edge of the HI distribution. They are the first BCDs with mass model fits to their rotation curves. The mass models include (1) a stellar distribution whose mass to light ratio is given by either a maximum disk model or by the optical colors (the “Bottema disk” model [5]); (2) the neutral ISM distribution; and (3) a dark matter halo. This halo is taken to be a pseudo-isothermal sphere whose free parameters are the central density $\rho_0$ and the core radius $R_c$. From these, the asymptotic rotational velocity and halo velocity dispersion can be calculated [11].

In both galaxies, DM dominates the mass distribution, even within the optical radius of the galaxy. In comparison, the stellar component has a mass equal to or less than the neutral gas disk.

Overall, the global dynamics of BCDs appear to be similar to dIs: they are dominated by rotating disks with normal looking RCs. A distinction between the two types is seen when the DM halo densities $\rho_0$ are compared, as shown in Fig. 3. Central densities found by maximum disk and Bottema disk fits are shown in separate panels. The comparison sample is taken from de Blok & McGaugh [5], and includes only galaxies with $M_B > -18$ mag. This comparison shows that NGC 1705 and NGC 2915 have two of the highest $\rho_0$ measurements of any dwarf galaxies. In order to check that these galaxies are typical, I crudely estimated $\rho_0$ from the central velocity gradient for 12 BCDs with published or unpublished RCs, and plotted them as circles at arbitrary $\mu_0$ in the top panel of Fig. 3. These estimates are upper limits, since the contribution of the baryonic components to the velocity gradients have not been removed. Nevertheless, the comparison indicates that NGC 1705 and NGC 2915 have normal $\rho_0$ for BCDs. Figure 3 shows a weak but noticeable correlation between log($\rho_0$) and $\mu_0$($B$), with higher surface brightness disks corresponding to higher $\rho_0$ halos. This result was first noted in dIs by de Blok & McGaugh [3].
4 Evolutionary Connections

The correlation in Fig. 2 can readily be explained by considering the response of a self gravitating disk immersed in a dominant DM halo core of constant density $\rho_0$, i.e. where the rotation curve is linearly rising. If the disk is maintained at constant stability parameter and the star formation rate per unit area scales with the gas density divided by the dynamical time $[10]$, then it is straightforward to show that the surface brightness should scale with $\rho_0$ $[18,19]$. This is consistent with the observed correlation, as shown by the dotted line in Fig. 2. A similar correlation between surface brightness and $\rho_0$ holds in the center of larger starburst galaxies $[17]$. However for them it is normal baryonic matter that dominates $\rho_0$ rather than DM. In essence, the central mass density determines the equilibrium star formation rate of the embedded disk.

Following from the discussion in Sec. refs:opt, the disk central intensity largely determines whether a dwarf galaxy is classified as a BCD or dI. The optical size of dwarfs seems to be limited to the core radius $R_c$. Hence, both DM halo parameters are important in governing the morphology of gas rich dwarfs.

Can there be evolution between dI and BCD classes? While some evolution in $\rho_0$ may be allowed, it is unlikely that there can be enough to change a typical dI into a typical BCD. That would require a 2.5 mag arcsec$^{-2}$ change in $\mu_0$, or equivalently, a factor of ten change in $\rho_0$. To do this with a mass loss or gain would require a 55% change in mass if the expansion or contraction is homologous $[19]$. The problem is that there isn’t that much baryonic mass in a dwarf galaxy. To effect this large of a change would require DM loss or gain. This is not feasible if DM is non-dissipative and feels only the force of gravity, as is usually assumed. I conclude that there is probably little dI $\leftrightarrow$ BCD evolution.

If the ISM were removed from a dI or BCD, it could still plausibly evolve into a dE galaxy. However, as noted in §3 even in a dwarf galaxy undergoing a strong starburst with a spectacular galactic wind (NGC 1705), the fractional loss of the ISM is modest. If this is typical, it would take on order of 10 bursts to expel all the ISM from a BCD. The bursts aren’t strong enough, and the ISM distributions are too flattened to allow a single burst expulsion of the ISM $[3]$. The demographics of dwarf galaxy morphologies point to an environmental component to their evolution. Gas rich dwarfs are found in low density environments where the frequency of external starburst triggers is low. They survive easily. The clock runs faster (more frequent triggers) in clusters, and in addition ram pressure stripping would accelerate the removal of gas from dwarfs, while tidal truncation of DM halos would assist galactic wind losses. Hence it is not surprising that gas poor dEs are found more often in clusters than the field.

5 Conclusions

We are now at a position to re-evaluate the Davies and Phillips $[4]$ scenario for dwarf galaxy evolution. The mechanisms they invoke have clearly been verified. Dwarf galaxies do experience starbursts and these can expel some of the
ISM. Mass expulsion can rival or surpass lock up into stars in regulating the
gas content of dwarfs. However, the results of any single burst are not so severe.
Cataclysmic bursts are not common at the present epoch, and the milder bursts
that are observed may not be sufficient to change a galaxy’s morphological clas-
sification. The morphology of a dwarf galaxy is largely set by its enveloping dark
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