Formation of blue compact dwarf galaxies from merging and interacting gas-rich dwarfs

Kenji Bekki

School of Physics, University of New South Wales, Sydney 2052, NSW, Australia

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ABSTRACT

We present the results of numerical simulations which show the formation of blue compact dwarf (BCD) galaxies from merging between very gas-rich dwarfs with extended H I gas discs. We show that dwarf–dwarf merging can trigger central starbursts and form massive compact cores dominated by young stellar populations. We also show that the pre-existing old stellar components in merger precursor dwarfs can become diffuse low surface brightness components after merging. The compact cores dominated by younger stellar populations and embedded in more diffusely distributed older ones can be morphologically classified as BCDs. Since new stars can be formed from gas transferred from the outer part of the extended gas discs of merger precursors, new stars can be very metal-poor ([Fe/H] < −1). Owing to very high gaseous pressure exceeding 10^5 k_B (where k_B is the Boltzmann constant) during merging, compact star clusters can be formed in forming BCDs. The BCDs formed from merging can still have extended H I gas discs surrounding their blue compact cores. We discuss whether tidal interaction of gas-rich dwarfs without merging can also form BCDs.

Key words: galaxies: dwarf – galaxies: kinematics and dynamics – galaxies: star clusters – galaxies: structure.

1 INTRODUCTION

Blue compact dwarf (BCD) galaxies are defined as dwarfs having \( M_B \geq -18 \) mag, optical sizes smaller than 1 kpc, and spectra similar to H II regions of spiral galaxies (Thuan & Martin 1981) and their formation and evolution processes have long been discussed by many authors. Some gas-rich BCDs dominated by very metal-poor, young stellar populations (e.g. I Zw 18) were once suggested to be undergoing their first starbursts (e.g. Searle, Sargent & Bagnuolo 1973; Aloisi, Tosi & Greggio 1999; Thuan, Izotov & Foltz 1999), recent observations have however confirmed that most of BCDs have underlying older stellar populations at least a few 10^9-yr old (e.g. James 1994; Cairós et al. 2001; Amorín et al. 2007). Although optical structures (Gil de Paz, Madore & Pevunova 2003), H I properties (van Zee, Skillman & Salzer 1998) and chemical abundances (e.g. Hunter & Hoffman 1999) in BCDs have been discussed in terms of evolutionary links between BCDs and other types of dwarfs such as dwarf spheroidal (dSphs), ellipticals (dEs) and irregulars (dIrrs), physical connections between these dwarfs remain unclear.

A growing number of observations have recently suggested that the origin of BCDs can be closely associated with galaxy merging between low-mass dwarfs (e.g. Noeske et al. 2001; Östlin et al. 2001). For example, Pustilnik et al. (2001) investigated environ-
effects (Bekki & Shioya 1999), hydrodynamics for strongly self-gravitating gas (Bekki 1997) and formation of globular clusters (GCs) and field stars (Bekki et al. 2002). This code enables us to investigate chemical and dynamical evolution of forming BCDs in a self-consistent manner. We adopt the Burkert profile (Burkert 1995) for the radial density profile of the dark matter halo of a dwarf because it can be consistent with rotation curve profiles of dwarfs (Burkert 1995). The total mass of the dark matter ($M_{\text{dm}}(r)$) for a dwarf is set to be $8.0 \times 10^9 M_{\odot}$ for all models, and the dark matter halo has a large core radius ($r_c$) of 3.5 kpc and the truncation radius of 3.4$r_c$ (Burkert 1995). The old stars in the dwarf are assumed to have either a disky distribution (referred to as ‘disc model’) or a spheroidal one (‘spherical model’).

The radial (R) and vertical (Z) density profiles of the initially thin disc are assumed to be proportional to $\exp\left(-R/R_0\right)$ with scalelength $R_0 = 1$ kpc and to $\text{sech}^2\left(Z/Z_0\right)$ with scalelength $Z_0 = 0.2R_0$, respectively. For the spheroidal models, the stellar spheroids are assumed to have the projected radial density profiles exactly the same as those for the stellar components in the above disc models. In both disc and spheroidal models, a dwarf has a thin gas disc and the gaseous disc is assumed to have the same scalelength as that of the stellar one. The size and mass ratios of the gaseous disc to the stellar one are set to be free parameters and described as $s_g$ and $f_g$, respectively: the size ($r_g$) and mass ($M_g$) of the gas disc are $s_g r_s$ and $f_g M_s$, respectively. The H I diameters of gas-rich galaxies are generally observed to be larger than their optical discs (Broeils & van Woerden 1994). A small fraction of low-luminosity galaxies have H I gas envelopes extending out to 4 to 7 $r_s$ (e.g. Hunter 1997) with H I mass-to-light ratios up to $\sim 20 M_{\odot}/L_{\odot}$ (Warren, Jerjen & Koribalski 2004). Guided by these observations, we investigate models with $1 \leq s_g \leq 4$ and $0.1 \leq f_g \leq 2$.

Star formation is modelled by converting the collisional gas particles into collisionless new stellar particles according to the algorithm of star formation described below. We adopt the Schmidt law (Schmidt 1959) with exponent $\gamma = 1.5$ ($1.0 < \gamma < 2.0$, Kennicutt 1998) as the controlling parameter of the rate of star formation. The stars formed from gas ‘new stars’ whereas stars initially within a disc are called ‘old stars’ throughout this letter. Chemical enrichment through star formation and supernova feedback is assumed to proceed both locally and instantaneously in this study. The values of chemical yield and return parameter are 0.002 and 0.3, respectively, and the initial gaseous metallicity is [Fe/H] = −1.6.

Nearby BCDs (e.g. NGC 1705) are observed to have compact young star clusters (SCs) that can finally evolve into GCs (e.g. Meurer 1993). We try to investigate whether BCDs formed from dwarf–dwarf merging and interaction can have SCs. We adopt a plausible assumption that if gas pressure ($P_{\text{gas}}$) can exceed a threshold pressure ($P_{\text{th}}$), such high pressure of interstellar medium can induce the global collapse of giant molecular clouds to form massive compact star clusters corresponding to SCs (Jog & Solomon 1992; Elmegreen & Efremov 1997). We show the results of the models with $P_{\text{th}} = 10^3 k_B$, where $k_B$ is Boltzmann’s constant. The present results do not depend so strongly on $P_{\text{th}}$ for $P_{\text{th}} = 10^5−10^6 k_B$. New stars formed from gas with $P_{\text{gas}} > 10^3 k_B$ are identified as SCs rather than field stars in this study. We mainly investigate mass fractions of SCs among all new stars for each model.

The mass ratio of the two merging or interacting dwarfs ($m_2$), the pericenter distance ($r_p$) and the eccentricity ($e_p$) are assumed to be free parameters. The orbit of the two dwarfs is set to be the $xy$ plane and the distance between the centre of mass of the two dIrrs is $20 kpc$. The spin of each galaxy in a merger is specified by two angles $\theta_i$ and $\phi_i$, where suffix $i$ is used to identify each galaxy. $\theta_i$ is the angle between the $z$ axis and the vector of the angular momentum of a disc. $\phi_i$ is the azimuthal angle measured from the $x$-axis to the projection of the angular momentum vector of a disc on to the $xy$ plane.

Although we run many models with different parameters with different $m_2$, $r_p$, $s_g$ and orbits of mergers, we show only four representative models (M1, M2, M3 and M4) with two different orbital configurations: the highly inclined prograde–retrograde (‘PR’) orbit with $r_p = 1.0 kpc$, $e_p = 1.0$, $\theta_1 = 30^\circ$, $\theta_2 = 120^\circ$, $\phi_1 = 90^\circ$, $\phi_2 = 30^\circ$ and the prograde–prograde (‘PP’) one with $r_p = 10.0 kpc$, $e_p = 1.1$, $\theta_1 = 0^\circ$, $\theta_2 = 0^\circ$, $\phi_1 = 0^\circ$, $\phi_2 = 0^\circ$. We show the results of the model M1 in detail because it shows typical behaviors of BCD formation from dwarf–dwarf merging in the present simulation. We also show the results of the model M2 and M3 in which two dwarfs are tidally interacting with each other without merging, because this comparison of the two models enables us to clarify how interacting galaxies can become BCDs. The parameter values for the four models are shown in the Table 1. The total particle number used in a major merger model is 220 000 for collisionless particles and 30 000 for collisional ones. The fixed gravitational softening length for dark matter, old and new stars, and gas are set to be 0.35, 0.04

Table 1. Model parameters for N-body simulations.

| Model | Morphology | $M_s^b$ | $r_s^c$ | $M_g^d$ | $s_g^e$ | Orbit type | $m_2^f$ | $e_p^g$ | $r_p^f$ | Comments |
|-------|------------|---------|---------|---------|---------|------------|---------|---------|---------|----------|
| M1    | Disc       | 0.4     | 1.25    | 0.8     | 4.0     | PR         | 0.5     | 1.0     | 1.0     | Merging  |
| M2    | Disc       | 1.0     | 5.00    | 0.1     | 1.0     | PP         | 1.0     | 1.0     | 1.0     | Interaction |
| M3    | Spheroid   | 1.0     | 5.00    | 0.1     | 1.0     | PP         | 1.0     | 1.0     | 1.0     | Interaction |
| M4    | Disc       | 0.4     | 1.25    | 0.04    | 4.0     | PR         | 0.5     | 1.0     | 1.0     | Gas-poor |

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and 0.135 kpc, respectively. We confirm that stellar and gaseous discs are stable in isolated models (i.e. with no merging and tidal interaction) even if gas mass fraction is quite large: this is due to the very extended gas discs in the present models.

3 RESULTS

Fig. 1 shows mass distributions of different components (old stars, gas and new stars) in the merging model M1 at two different epochs with star formation rate (SFR) of 1.05 $M_\odot$ yr$^{-1}$ and 0.03 $M_\odot$ yr$^{-1}$. SFR reaches its maximum value of 4.13 $M_\odot$ yr$^{-1}$ and about 80 per cent of initial gas mass is consumed within 1.3 Gyr. In the late stage of merging between two gas-rich dwarfs with extended gas discs ($T = 0.50$ Gyr), nuclear starbursts can be triggered owing to efficient inwards transfer of gas from the outer H I discs of the merger progenitor dwarfs. As a result of nuclear starbursts, the compact core dominated by young stars can be formed and embedded in old stars and gas.

The spatial distribution of old stars clearly shows a disturbed morphology in the outer part of the merger ($T = 0.50$ Gyr). If the stellar population synthesis models for metallicities of [Fe/H] = −1.28 and ages of 0.5 Gyr by Vazdekis et al. (1996) are applied to the central core dominated by young stars, then $B - R$ is estimated to be −0.6, which is consistent with the observed range of $B - R$ in BCDs (Gil de Paz et al. 2003). This merger with a blue compact core dominated by young stars and an outer disturbed morphology can be thus identified as a BCD.

Fig. 1 clearly shows that after strong starbursts, the dwarf–dwarf merger can soon get dynamically relaxed to form a flattened spheroid with a central compact core and a H I envelope ($T = 1.33$ Gyr). The H I envelope with the mass of $1.6 \times 10^3$ $M_\odot$ (i.e. $M_g/M_* = 0.27$) has a disky distribution with its outer part strongly warped. The SFR after strong starbursts can still become relatively high (e.g. $\sim 0.1$ $M_\odot$ yr$^{-1}$ at $T = 1.2$ Gyr) in a sporadic way owing to the presence of the gas disc. This merger remnant with a compact core, a more regular morphology and a higher SFR therefore can be also identified as a BCD.

The projected radial density profiles of old and new stars shown in Fig. 2 clearly demonstrate that the merger remnant is dominated by new stars formed from nuclear starbursts in the central 1 kpc. If we adopt $M_*/L_B$ (i.e. ratio of stellar mass-to-light in $B$ band) of 1.0, $B$-band surface brightness ($\mu_B$) distribution of old (new) stars ranges from $\sim 24$ ($\sim 22$) mag arcsec$^{-2}$ at $R \sim 0.1$ kpc to $\sim 29$ ($\sim 29$) mag arcsec$^{-2}$ at $R \sim 2$ kpc in this model. Since $M_*/L_B$ is significantly smaller than 1 for stars younger than 1 Gyr (e.g. Vazdekis et al. 1996), $\mu_B$ in the central region of the simulated BCD would be significantly higher than the above.

Fig. 3 shows that metallicities in [Fe/H] for new stars within the central 5 kpc of the merger remnant in the model M1. The 1σ dispersion in the metallicities for each radial bin is shown by an error bar. The mean metallicity ($\langle z_m \rangle$) of new stars is [Fe/H] = −0.93 for this model and $z_m$ depends totally on the adopted initial gaseous metallicities and chemical yield parameters in the present models.
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if the underlying old stars have spherical distributions rather than discs. The interacting dwarf with a compact core in the model M2 shows an exponential radial density profile in its outer diffuse stellar component dominated by old stars. The time-scale for which SFR is rather high ($>0.1 \, \text{M}_\odot \, \text{yr}^{-1}$) in merging and interacting dwarfs is quite short (an order of $\sim 0.1$ Gyr) in the present models. Therefore, the time-scale for merging and interacting dwarfs to be observationally identified as BCDs with very strong emission lines can also be short (an order of $\sim 0.1$ Gyr).

The present models predict that gaseous pressure during starbursts triggered by galaxy interaction and merging can become very high ($P_{\text{gas}} > 10^5 k_B$) so that SCs can be formed in BCDs. For example, the mass fraction of SCs is 0.22 in the model M1, though not all of these may evolve into GCs finally owing to internal and external destruction processes after their formation. This result clearly suggests that BCDs formed from dwarf–dwarf merging can contain young GCs owing to tidal compression of gas during the merging. Furthermore, it is highly likely that nuclear star clusters in BCDs can be formed from nuclear starbursts during dwarf–dwarf merging. We thus suggest that the observed presence of young SCs and blue stellar nuclei in BCDs is possible evidence for BCD formation via dwarf–dwarf merging.

Lastly, we describe the results of the gas-poor model M4 in which a BCD cannot be formed. Although the SFR can become high ($\sim 0.6 \, \text{M}_\odot \, \text{yr}^{-1}$) in the final phase of dwarf–dwarf merging, the total mass of new stars formed in the triggered starbursts is significantly smaller ($\sim 4 \times 10^7 \, \text{M}_\odot$) than that of old ones ($\sim 6 \times 10^8 \, \text{M}_\odot$). As a result of this, the central part of the merger remnant cannot be dominated by new stars. As shown in Fig. 5, surface density of old stars within the central 1 kpc of the remnant is systematically much higher than that of new ones: more than an order of magnitude differences between old and new stars at $R \sim 1$ kpc. The low-mass density of new stars, combined with a small amount of gas-mass ($\sim 2 \times 10^7 \, \text{M}_\odot$), cannot allow us to claim that the remnant of the gas-poor merger in this model is classified as a BCD. These results imply that only gas-rich dwarf–dwarf mergers can finally evolve into BCDs.

4 DISCUSSION AND CONCLUSIONS

This study has shown that BCDs can be mergers between dwarfs with larger fractions of gas and extended gas discs. This study has also shown that (i) BCDs appear to be compact because the compact cores dominated by young stellar populations can be formed from starbursts triggered by merging and (ii) they also appear to be very blue because the dominant stellar populations are young and formed from metal-poor gas during merging. Furthermore, our models have shown that extended H i gas discs of merger progenitor dwarfs are responsible for the formation of BCDs with massive H i envelopes surrounding blue compact cores.

Recent H i observations have found that (i) some faint galaxies have high gas-mass fractions ($3 < M_{\text{HI}}/L_B < 27$) and (ii) fainter galaxies are more likely to have higher $M_{\text{HI}}/L_B$ (e.g. Warren, Jerjen & Koribalski 2006). Furthermore, the Faint Irregular Galaxies GMRT Survey (FIGGS) has recently revealed that the mean value of H i-disc to stellar-disc ratios ($s_d$) is about 2.4 for dIrrs with a median $M_{\text{B}} \sim -13$ mag (Begum et al. 2008). These observations suggest that galaxy merging that forms BCDs (i.e. mergers with high $M_{\text{HI}}/L_B$ or $s_d$ and large $s_d$) cannot be so rare among all types of dwarf–dwarf merging.

Although some BCDs with very metal-poor and young stellar populations were observationally suggested to be true young galaxies that are currently forming (e.g. Thuan et al. 1999), they have now being observed to have older stellar populations (e.g. Aloisi et al. 2007). This study has shown that young stellar populations in BCDs can be very metal-poor because they originate from extended gas discs with possibly pristine gas in merger precursor dwarfs: the presence of very metal-poor stellar populations in BCDs does not necessarily imply the very early epochs of their formation.

Gil de Paz et al. (2003) investigated morphological types for 111 BCDs with Hα emission and revealed that only 10 ($\sim 9$ per cent) can be classified as `il, M` (i.e. mergers). Our numerical results suggest that the `il` BCDs with irregular outer haloes and off-centre nuclei, which consist of 35 per cent of the BCDs (Gil de Paz et al. 2003), can be formed from dwarf–dwarf merging. It would also be possible that even `il` BCDs with outer diffuse elliptical haloes yet without clear signs of merging are merger remnants with their outer haloes already dynamically relaxed. Although `il C` BCDs with commentary morphologies can be ongoing mergers with long tidal tails viewed from edge-on, such morphologies can be formed from other physical processes such as ram pressure stripping.

The present simulations have shown that evolution from BCDs formed from dwarf–dwarf merging into gas-poor dEs is highly unlikely owing to the presence of extended gas discs in the BCDs. Tajiri & Kamaya (2002) showed that morphological evolution from BCDs with H i envelope into gas-poor dEs is unlikely because stellar feedback effects in BCDs are not strong enough to blow off their H i envelope. This observation combined with the present numerical
results therefore implies that BCDs are likely to evolve into gas-rich, nucleated dIrrs after significant fading of their blue compact cores. Papaderos et al. (1996) found significant differences in optical structures between BCDs and dIrrs, and thus suggested that BCDs can evolve into dIrrs only if BCDs can change optical structures of their underlying stellar populations. By using fully consistent stellar population models combined with chemodynamical simulations of BCD formation in our future papers, we discuss in detail whether the optical structures of BCDs formed from merging can change owing to fading of their young stellar populations so that the final structures are more similar to those of dIrrs (Papaderos et al. 1996).

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