Star-Formation of Blue Compact Dwarf Galaxies*

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Abstract

Color-magnitude diagrams (CMDs) of Blue Compact Dwarf (BCD) galaxies are the most direct probes of their star-formation histories (SFH). Over half a dozen very nearby BCDs now have good quality CMDs obtained with HST. We find that BCDs generally contain stars which are at least 1 Gyr old, and that their star-formation rates (SFR) have been quite continuous over the recent Gyr. These BCDs generally also show rather low rates of active star formation, 10^{-3}–10^{-2} $M_\odot$ yr^{-1}. We investigate the present-day SFR of the about 50 BCDs in the Izotov & Thuan (1999) sample using infrared and radio data. The SFRs in the Izotov & Thuan sample span almost five orders of magnitude, with a median value of about $0.2\,M_\odot$ yr^{-1}. While BCDs with high SFRs, a few ten $M_\odot$ yr^{-1}, do exist at comparatively large distances, we find that the most nearby BCDs tend to have the smallest SFRs. This explains why the SFRs in the BCDs resolved with HST are so low; these BCDs were necessarily selected to be very nearby objects. We also present and discuss a fit of 12+log(O/H) vs. log(SFR).

1 The Ages of BCDs

The possibility that genuinely young galaxies might inhabit our local Universe has been considered since the pioneering work of Sargent & Searle (1970). "Isolated extragalactic H II regions", nowadays referred to as BCDs, were proposed to be either primeval galaxies in the process of forming their very first stars in the present epoch, or alternatively, old galaxies which currently light up due to intense star formation.

Our team has made use of the excellent spatial resolution of the HST to resolve several very nearby BCDs into individual stars: NGC 6789 (3.6±0.2 Mpc, see Drozdovsky et al. in this volume), Mrk 178 (≥4.2±0.5 Mpc, Schulte-Ladbeck et al. 2000a), VII Zw 403 (4.4±0.2 Mpc, Schulte-Ladbeck et al. 1999), I Zw 36 (≥5.8±0.4 Mpc, Schulte-Ladbeck et al. 2001), and UGCA 290 (6.7±0.4 Mpc, Crone et al. 2000, and this volume). We have also commented on the CMDs of the extremely metal-poor BCDs I Zw 18 and SBS 1415+437 (Schulte-Ladbeck et al. 2000b). The case of NGC 1705 is discussed by Annibali et al. and Sabbi et al. in this volume.

We have yet to observe a BCD in which the distribution of stars on the CMD is consistent with a single, instantaneous "delta function"-like burst of star formation, or of a single short burst which was preceded by a Gyr-long period of quiescence. In all cases, resolved stars are seen all the way down to the limiting magnitudes of the photometry. The oldest stars seen are those in the red

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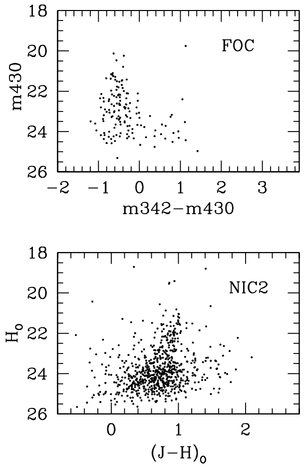


Figure 1: The near-UV—optical, FOC CMD of I Zw 36 from Deharveng et al. (1994) is compared with our near-IR, NIC2 CMD. Notice that the blue plume containing main sequence and blue supergiant stars dominates the near-UV—optical CMD, while the red plume containing red supergiants, asymptotic giants and red giants is the most prominent feature of the near-IR CMD. Whereas the former might suggest an instantaneous burst of star formation, the latter indicates a long and continuous history of star formation, dating back at least about 2 Gyr.

tangle; and they typically have ages of about 1 Gyr or above, indicating that none of the BCDs resolved into stars is a primeval galaxy.

2 The Star-Formation Modes of BCDs

We also do not find that the SFHs of BCDs have been highly episodic, and we illustrate this result using our case study of I Zw 36 (Schulte-Ladbeck et al. 2001). The first BCD resolved with HST was I Zw 36 (Deharveng et al. 1994), and we reproduce their CMD in Fig. 1. Also shown is the near-IR CMD from our own HST observations. The near-UV—optical CMD of I Zw 36 lacks evolved red supergiants. Indeed, being dominated by the blue plume of main sequence and blue supergiant stars, this CMD can be interpreted as showing an instantaneous (less than 12 Myr old and on-going) bout of star formation. The lack of red supergiants on the near-UV—optical CMD cannot, however, imply a discontinuous star-formation history, since the near-IR CMD shows such a copious population of red stars. This suggests the SFH extents to earlier times than 12 Myr ago, and that observational biases such as color bias must be taken into consideration before conclusions about the star-formation mode (SFM) may be reached. While we can rule out that I Zw 36 is primeval, we cannot say whether it is just a few Gyrs of age, or whether it is an ancient (older than 10 Gyr) galaxy.

In Schulte-Ladbeck et al. (2001), we present modeling of the CMD of I Zw 36 with the help of synthetic CMDs. A main result of our modeling is that if we allow short stops (10 — 100 Myr) in recent SFH (within the last Gyr), we can still produce CMDs which match the data. However, once star formation is interrupted by several 100 Myr, the morphology of the CMD changes so drastically that we find long gaps with zero star formation cannot be hidden in the data. A moderate modulation in the recent SFR up or down – bursts or gasps – is consistent with our data. We can also glean some information about possible, ancient star formation from the red giants of I Zw 36. If we *assume* an age of 15 Gyr, and partition the CMD into the stars born from 0-1 Gyr, and from 1-15 Gyr; we derive $SFR/<SFR>_{past}$ is about 13. We previously determined a similar birthrate parameter for Mrk 178 (Schulte-Ladbeck et al. 2000a).

Extended periods of high- and low-states of star formation, which we infer from these model CMDs to be viable SFHs, would alleviate the problem of the missing quiescent counterparts of BCDs in the local Universe. This SFM would also have implications concerning models in which faint blue excess galaxies are late-forming, star-bursting dwarfs.

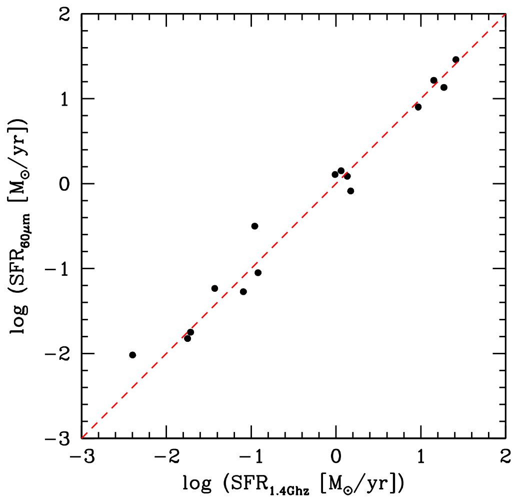


Figure 2: A comparison of IRAS-based SFRs and NVSS-based SFRs for the few BCDs in the Izotov & Thuan sample for which both 60 μm and 1.4 GHz fluxes are available. The measurements are in good agreement. They illustrate that a wide range of SFRs is displayed by galaxies in the Izotov & Thuan sample.

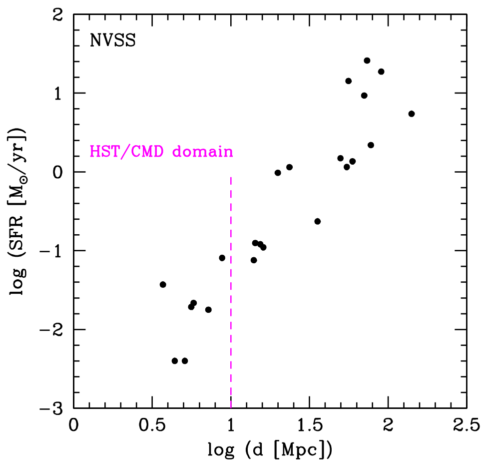
3 The Star-Formation Rates of BCDs

The galaxies which we studied in detail with the aid of CMDs always appear to exhibit rather low SFRs, a few times 10^{-3} $M_\odot$ yr^{-1} to several 10^{-2} $M_\odot$ yr^{-1}. On the other hand, BCDs are often referred to as intensely bursting systems. As we reviewed the literature, we were surprised by how few actual measurements of the SFR we found. Would the systematic investigation of a larger sample of BCDs reveal that the SFRs of BCDs are much smaller than hitherto believed?

We decided to investigate the SFRs in the well-known BCD sample of Izotov & Thuan (1999). The galaxies in this sample represent the best-studied BCDs; they have well-determined metallicities, and were used to derive the primordial He abundance. We used two public databases to obtain fluxes. We culled 60 μm fluxes from the IRAS catalog, and 1.4 GHz fluxes from the NVSS database (Condon et al. 1998). We converted fluxes to luminosities assuming an H_o of 75 km/s/Mpc, a Virgo distance of 15.9 Mpc, and corrected for Virgo-centric infall. The fluxes were converted to SFRs using the Salpeter IMF with mass range 0.1-100 $M_\odot$. We also assumed that the IR light results from thermal re-radiation of the UV flux of young massive stars by dust grains, while the radio flux results from non-thermal radiation produced by relativistic electrons that are accelerated when massive stars explode as supernovae (Condon 1992). Fig. 2 shows that we obtain consistent results from IR and radio fluxes.

We find that the SFRs of the BCDs in this famous sample span over four orders of magnitude, from approximately a few times 10^{-3} to several 10^1 $M_\odot$ yr^{-1}. BCDs with high SFRs do indeed exist. However, the median SFR of the sample is only $0.22\,M_\odot$ yr^{-1}.

An understanding of why the HST-resolved BCDs are objects with very small SFRs can be developed with the help of Fig. 3. Fig. 3 shows that the observed SFRs increase almost linearly with BCD distance. This is not a luminosity-density evolution-type (aka, a "Madau plot"-type) result. Rather, this behavior comes about by observational biases. Assume that there are more dwarfs with low SFRs than with high SFRs in a given volume of space. Then, for the lowest BCD distances, since the volume sampled is very small, there is only a very small chance to detect a galaxy with a high SFR. At large distances, on the other hand, the volume is large enough that we should see both, galaxies with low and high SFRs, but here the flux limit of the survey cuts off those BCDs which have low SFRs. Fig. 3 then suggests that among the well-known BCDs, all of those BCDs sufficiently nearby to be resolved to deep limiting magnitudes with HST, 10 Mpc



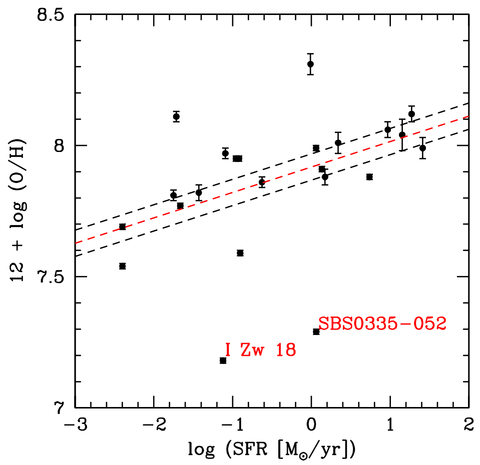


Figure 3: The NVSS SFRs of the Izotov & Thuan BCDs is plotted as a function of their distance in Mpc. The very nearby BCDs which can be resolved into single stars with HST all have very small SFRs.

Figure 4: The oxygen abundance derived by Izotov & Thuan is shown as a function of the NVSS-based SFR. While there is an obvious trend for BCDs with higher oxygen abundances to also show higher SFRs, there is scatter as well. The most metal-poor BCDs appear removed from the general trend even after allowing for scatter.

or so, have very small SFRs. This is consistent with our finding of low SFRs from CMDs. Those galaxies were selected for HST study just because they are so very nearby. (We note that Tosi in this volume points to an exceptionally high SFR in the nearby dwarf Irregular NGC 1569. However, since NGC 1569 is not classed a BCD, it is not part of the above sample.)

4 The Chemical Evolution of BCDs

A major difficulty of chemical evolution modelling of BCDs has been to reproduce their low metal abundances in the presence of relatively high SFRs. In Fig. 4, we show the oxygen abundance of the ionized interstellar medium, with 12+log(O/H) values taken from Izotov & Thuan, as a function of the radio-based SFR. There is a general trend of increasing oxygen abundance with increasing SFR. However, there is also some scatter about this relation. In particular, the two most extremely oxygen-poor galaxies, I Zw 18 and SBS 0335-052, whose oxygen abundances have very small errors, appear very far removed from the general trend.

We modeled the O/H vs. SFR trend with a weighted linear least-squares fit. (No errors for the SFR were assumed because we really don't know errors for the distances.) A very good χ^2 was achieved when we left out the I Zw 18 and SBS 0335-052 data (else the linear fit was giving a slope that was much too steep). The fit plotted in Fig. 4 is $\mathbf{12 + \log(O/H) = 0.097 \log(SFR) + 7.918}$. We also show lines at $\pm$ 1 σ, which use the uncertainty in the intercept of an unweighted linear least-squares fit. We see that 65% of the data points lie within these 1 σ limits. However, I Zw 18 and SBS 0335-05 appear to have much too low an oxygen abundance given their present-day SFR. Some galaxies also have high O abundances for their present-day SFRs. Some of the scatter may perhaps be reduced with better distances.

The simplest explanation for a correlation of the oxygen abundance with the SFR is to assume that the same supernovae which provide the 1.4 GHz luminosity from which we gauge the SFR are also responsible for "polluting" their environment with oxygen: the higher the SFR, the more SNeII, hence the higher the O/H ratio. The large outliers at low oxygen abundance, I Zw 18 and SBS 0335-052, could perhaps be understood as those BCDs which are most affected by metal-enhanced galactic winds (Marconi, Mateucci & Tosi 1994, Ferrara& Tolstoy 2000); their high SFRs lead to intense SN-driven winds capable of preferentially ejecting their freshly-made oxygen.

We must ask, however, whether the SFR as well as the oxygen abundance measured represent the present-day values of these quantities. We infer from the tight correlation between the radio- and infrared-based SFRs seen in Fig. 2 that the 1.4 GHz fluxes used for Fig. 4 are indeed a measure of present-day SFRs. As regards the oxygen abundance, Kobulnicky & Skillman (1996) have argued that their measurements of individual H II regions in dwarf Irregular galaxies suggest localized chemical enrichment from the active star formation generally does not occur. They conclude that the oxyen abundance that we measure today is a global oxygen abundance which has built up over time, or $<\mathrm{O/H}>_{past}$.

If the relation seen in Fig. 4 is not due to self pollution, than its interpretation is less straightforward. The implication is that $<\mathrm{O/H}>_{past}$ correlates with SFR, in other words, the higher the past SFR and the consequent O enrichment of the interstellar medium, the higher the SFR now. This suggests that BCDs on the O/H vs. SFR relation may have very similar values of $\mathrm{SFR}/<\mathrm{SFR}>_{past}$. Our synthetic CMD studies for Mrk 178 and I Zw 36 suggest that $\mathrm{SFR}/<\mathrm{SFR}>_{past}$ for these two BCDs is indeed similar. However, little is known about $\mathrm{SFR}/<\mathrm{SFR}>_{past}$ for BCDs as a whole. Scatter in the O/H vs. SFR trend, either up or down, could be introduced by allowing for extreme values for $\mathrm{SFR}/<\mathrm{SFR}>_{past}$. For instance, a low time-averaged enrichment in oxygen may have been the result of a very low $<\mathrm{SFR}>_{past}$ in the early history of BCDs ("slowly cooking galaxies" as proposed for I Zw 18 by Legrand et al. 2000, see also Henry, Edmunds, & Köppen 2000).

5 Conclusions

The results of our CMD studies challenge ages of BCDs based on chemical-evolution modelling (e.g., Izotov & Thuan 1999), by allowing for the existence of gas-rich and metal-poor galaxies which are nevertheless not young. An alternative to the young galaxy hypothesis is that BCDs are slowly evolving galaxies and as such, have remained very deficient in oxygen despite their age. We speculate that such slowly evolving galaxies may maintain low metallicities and remain gas rich over much of the Hubble time, defying any simple age-metallicity relation.

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