Stellar Feedback, Dark Matter and Dwarfs Evolution

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Abstract

Supernovae strongly regulate several structural properties of dwarf galaxies. In particular, they govern the metal enrichment and the energy budget of the ISM; they might induce partial (blowout) or total (blowaway) gas removal from the galaxy; they also regulate the pressure of the ISM and consequently the morphology of the galactic gaseous body. Significant amounts of dark matter may play an equally important role: the dark matter gravitational potential tends to concentrate baryons towards the center, thus enhancing both star formation and metal production rates. Here we outline the interplay between these two types of physical processes and show how the cosmological evolution of dwarfs has been affected by them.

1 Introduction

Dwarf galaxies are classified in four basic types: *(i)* Dwarf Irregular (dI) galaxies are usually unstructured gas rich systems with varying levels of star formation; *(ii)* Blue Compact Dwarf (BCD) galaxies are gas rich systems dominated by very active star formation, and resembling massive H II regions seen in large galaxies. *(iii)* Dwarf Spheroidal (dSph) galaxies usually have no gas in their center down to very low limits (Knapp *et al.* 1978); their stellar distribution is similar to that of globular clusters, although less centrally concentrated; *(iv)* Dwarf Elliptical (dE) galaxies look similar to their namesake elliptical galaxies. Thus, broadly speaking, there are two classes of dwarf galaxies. Late-type (dI and BCD) are star forming systems.

Several evolutionary schemes transforming the first class into the second have been proposed. Einasto *et al.* (1974), and later on Lin & Faber (1983), pointed out that since early type dwarfs are often found as satellites of large galaxies, ram pressure stripping in such a high density environment could provide an efficient mechanism to remove all the gas from a galaxy, although Binggeli (1994) gives a list of arguments against it. One scenario for the dI $\rightarrow$ dE transition was proposed by Davies & Phillips (1988), who postulated that the gas, instead of being swept away by some transport mechanism, could have been consumed by astration.

Given that the major differences between the two classes reside in their star formation histories, it is important to determine the effects of star formation on the ISM. Among these effects, the most important one is very likely the energy injection from massive stars. This has at least three different consequences: *(i)* the H I kinematics might become very disturbed; *(ii)* due to their shallow potential wells, dwarfs can lose their gas, in a process that we will refer to in this paper as blowaway. *(iii)* the metallicity range of dwarfs must be consistent with what is inferred from massive star energetics.

In particular, Dekel & Silk (1986) concluded that in order to reproduce the surface brightness and metallicity decline towards low masses, a significant gas loss in a dominant DM halo potential has to take place, with an upper critical halo circular velocity of ~ 100 km s^{-1}.

Dark matter is the second important ingredient necessary to properly understand dwarf galaxy evolution. Data on the DM content of low mass galaxies, although slowly accumulating are still scarce, and often difficult to interpret. The M/L ratios have been shown to vary between 5.7 and 94

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(e.g. Mateo *et al.* 1993, Pryor 1996), confirming the perception that small objects tend to be dark matter dominated. The same conclusion can be reached from rotation curve studies: although exploring the mass distribution only down to relatively large values, a clear trend of increasing dark-to-visible mass ratios with decreasing mass is seen (Mateo 1993).

Here we present results of including the above processes in models for the evolution of dwarfs, which are mostly based on the findings of Ferrara & Tolstoy (2000; FT), to which we defer the interested reader for a full description and discussion.

2 Energy Budget of the ISM in Dwarfs

Supernova explosions may contribute to drive a substantial mass loss from the galaxy. In order that mass previously located inside the region affected by the (multiple) explosion is ejected from the galaxy, the velocity v_b of the expanding shell has to be larger than the escape velocity from the galaxy, v_e. Assuming a modified isothermal distribution of the dark matter in the halo of total mass M_h, this translates into a blowout condition shown in Fig. 1. This depends weakly on the value of the dark-to-visible mass ratio $\phi = M_h/M_g$ of the galaxy (this dependece has been investigated in great detail by Persic *et al.* 1996; their relation is shown by the curve labelled PSS), where M_g is the galactic gas mass. To the left of such curve gas is ejected from the potential well of the galaxy, whereas more massive galaxies might undergo "galactic fountain" phases, with the gas temporarily stored in the halo.

By definition, the blowout phenomenon involves a limited fraction of the parent galaxy mass, the one contained in cavites created by the explosion. A much more disruptive event may occur, *i.e.* the blowaway, in which the gas content of the galaxy is completely expelled and lost to the intergalactic medium. The requirement for the blowaway to take place is that the momentum of the SN-driven shell at a given galactocentric radius ϖ_c is larger than the momentum necessary to accelerate the gas outside ϖ_c at a velocity larger than v_e. FT have then derived the following blowaway condition, graphically displayed in Fig. 1:

$$v_b \gtrsim (\epsilon - a)^2 a^{-2} e^{3/2} v_e, \tag{1}$$

with $a \simeq 2/3$ and ϵ being the major-to-minor axis ratio of the galaxy. Hence, flatter galaxies (large ϵ values) preferentially undergo blowout, whereas rounder ones are more likely to be blown-away. These results are supported by the extended numerical simulations of Mac Low & Ferrara (1999). This work also showed that whereas in a blowout heavy elements are ejected with efficiencies larger than 90% in most cases, the cold HI is much less coupled to the outflow and $\xi \lesssim 10\%$ can escape from the galaxy. Although only a fraction $\eta \simeq 3\%$ of the total explosion energy E_0 can be transformed in kinetic form, this energy amount is enough to explain the level of turbulent motions that we observe in galaxies. Norman & Ferrara (1996) calculated the detailed grand source function for the conventional sources of turbulence from supernovae, superbubbles, stellar winds and H II regions. The main conclusion is that superbubbles are the main contributors to interstellar turbulence. In addition, from the study of the general properties of the turbulent spectrum using an approach based on a spectral transfer equation derived from the hydrodynamic Kovasznay approximation, they conclude that the turbulent pressure calculated from the grand source function is $\sim 10 - 100$ larger than the thermal one. Turbulent energy injected by SN explosions can then be dissipated via radiative losses during fluid element (supersonic) collisions.

The rate at which the kinetic energy density in the ISM, ϵ_k, increases following SN explosions is

$$\dot{\epsilon}^+ = \frac{\rho}{M_g} \left[\eta E_0 \gamma (1 - \xi)\right] \tag{2}$$

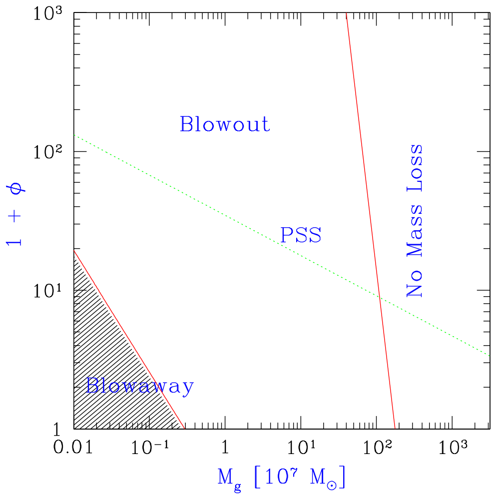

Figure 1: Blowout/ Blowaway regions in the $\phi - M_g$ plane. Also shown is the Persic *et al.* relation (dotted line).

where ρ is the mean ISM gas density. The dissipation rate per unit volume $\dot{\epsilon}^-$ is the product of three quantities: the energy lost per collision, ΔE, the number density of clouds in the galaxy, N_c, and the cloud-cloud collision frequency, ω_c. The maximum energy loss per collision ΔE takes place when the collision is inelastic: for an ensamble of equal clouds of mass m moving with velocity dispersion σ, it follows that $\Delta E = m\sigma^2$, *i.e.* all the initial kinetic energy is lost. Are cloud collisions in dwarfs truly inelastic ? The elasticity of collisions depends both on metallicity and cloud size (Ricotti *et al.* 1997); nevertheless, most conditions are found to lead to inelastic collisions in the absence of a magnetic field. In two subsequent papers, Miniati *et al.* (1997, 1999) pointed out that even a relatively weak magnetic field makes collisions much more elastic. To roughly take into account this effect, we have adopted a reduction factor $b_1 \lesssim 1$ in the energy dissipation rate. Hence it is

$$\dot{\epsilon}^- = b_1 N_c \omega_c \Delta E \tag{3}$$

Equating the two rates one obtains the equilibrium value for σ:

$$\sigma_{eq} \simeq 4.5 b_1^{-1/4} \phi^{1/8} M_{g,7}^{0.08} \quad \mathrm{km\ s^{-1}}. \tag{4}$$

The equilibrium value of the cloud velocity dispersion increases with galactic gas mass as a result of the more vigorous star formation activity occurring in those objects. Also, the spread introduced by the different DM content is about a factor 2 only for a given galactic mass. This allows us to conclude that the *gas velocity dispersion is only mildly influenced by the underlying gravitational potential of the galaxy.* Instead, the relatively similar values commonly observed in galaxies greatly differing in mass, suggest that self-regulation is at work through the processes described in this Section.

3 Specific Predictions

We now turn to the description of some predictions of the model developed by FT on dwarfs galaxies. All these results point towards the fact that most observable properties of dwarfs can be understood as the result of the interplay between the stellar feedback (*i.e.* outflows and turbulent power injection) and the dark matter – dominated gravitational potential. The results are compared with a sample of 41 gas rich galaxies taken from Skillman *et al.* (1989) and van Zee *et al.* (1997a,b); the complete list of objects is given in FT. In addition, we have also model in even greater detail the nearby dI galaxy Leo A, for which a detailed star formtion history based on color-magnitude

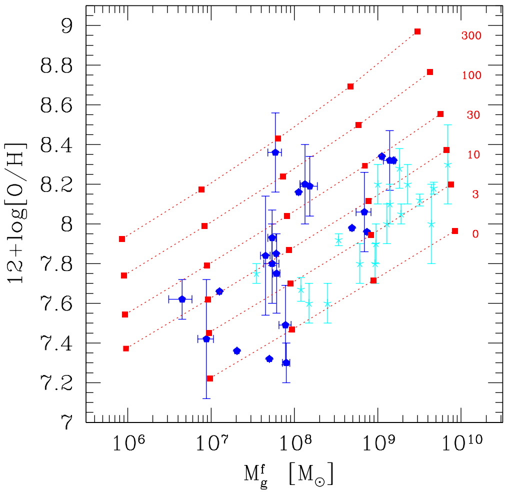

Figure 2: Model results for the oxygen abundance as a function of the final gas mass M_g^f for different values of $\phi = 0, 3, 10, 30, 100, 300$ (squares); points show the data from the Skillman et al. (1989) (*pentagons*) and van Zee et al. (1997a,b) (*stars*) samples.

diagrams has been derived. The results for this case are discussed at length in FT and we do not repeat them here.

3.1 Oxygen Abundance

Fig. 2 shows a comparison between data and the model results for the oxygen abundance as a function of the final gas mass M_g^f for different values of ϕ. As a general trend, the oxygen abundance in dwarf galaxies increases with M_g^f: this behavior is correctly reproduced by our results. However, for a given M_g^f, there is a considerable spread in the metallicity data. This can be understood as an effect of the different DM content, where higher dark-to-visible mass ratios produce higher final values of oxygen abundance, $X_{\rm O}$. This is due to the fact that as the DM content is increased at fixed gas mass, the gas tends to be compressed towards the central regions by the stronger gravitational potential. As a consequence of the higher density, the star formation process is favored and its rate increased. For similar reasons, adding DM makes outflows, and hence oxygen mass loss, less efficient.

From Fig. 2 it appears that almost all sample galaxies can be inferred to have dark-to-visible mass ratio $\phi \simeq 0 - 30$ (although about 65% of the objects have $\phi \leq 10$ as shown by the observed distribution in Fig. 2), in order to explain the observed oxygen abundances. The above range brackets the value $\phi \approx 20$ expected from the cosmological value.

We also predict the existence of a lower limit for the oxygen abundance of very low mass ($M_g^f \lesssim 10^7 M_\odot$) dwarfs: almost independently of ϕ, $X_{\rm O}^{min} \approx 0.02$ (*i.e.* $12 + \log({\rm O/H}) \approx 7.2$). This lower limit is set by the minimum amount of DM necessary to avoid the blowaway, which results in the minimum metallicity. It is interesting to note that there is a group of objects with masses around $10^7 M_\odot$ that should be critically close to fulfill the blowaway condition. The fact that these objects are among the faintest star forming objects known is consistent with the destruction of even smaller galaxies in the past.

3.2 Mass Outflow Rate

Fig. 3 shows the mass outflow rate $\langle \dot{M}_w \rangle$, averaged over the galaxy lifetime as a function of galactic gas mass at the present time. The mass loss rate is typically in the range $10^{-5} - 0.04\ M_\odot\ {\rm yr}^{-1}$ and it is a rather steep function of gas mass peaking at $M_g^f \approx$ few $\times\, 10^8 M_\odot$. The peak is the product of two effects: on the one hand the galaxy has to be sufficiently gas rich to form enough massive

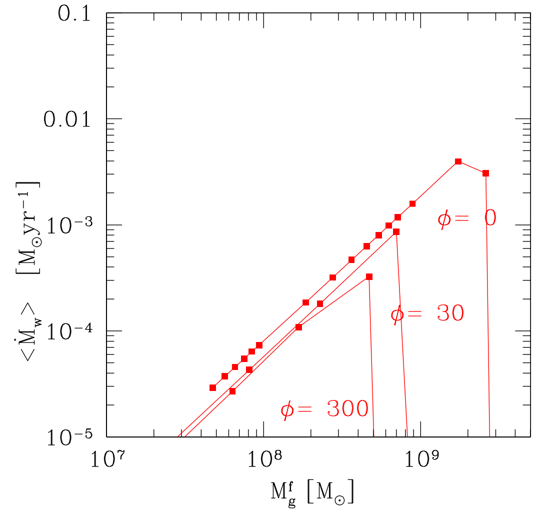

Figure 3: Time-averaged mass outflow rate $\langle \dot{M}_w \rangle$ as a function of the final gas mass M_g^f for three different values of $\phi = 0, 30, 300$.

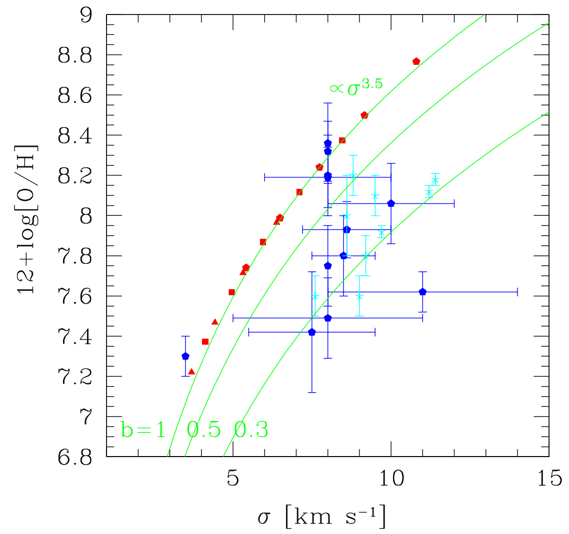

Figure 4: Relation between oxygen abundance and gas velocity dispersion σ for $\phi = 0$ (triangles), $\phi = 10$ (squares), $\phi = 100$ (pentagons). A fit to the relation is also shown for three values of the magnetic reduction factor $b_1 = 1.0, 0.5, 0.3$ (solid lines). Data points are from the Skillman et al. (pentagons) and van Zee et al. (stars) sample.

stars to power the outflow; on the other hand, larger masses correspond to higher escape velocities which make the outflow increasingly difficult. For a given galaxy gas mass, $\langle \dot{M}_w \rangle$ is only weakly dependent on the dark-to-visible mass ratio, as can be appreciated from Fig. 3. Consistently with the above interpretation, $\langle \dot{M}_w \rangle$ decreases with increasing ϕ; however, the differences between the cases $\phi = 0$ and $\phi = 300$ are less than a factor $\lesssim 10$ in the mass range considered; at the high mass end the larger v_e quenches the blowout, as expected (see Fig. 1). Galaxies of mass few $\times\, 10^8 M_\odot$ are therefore the major pollutants of the IGM with both mass and heavy elements.

3.3 Gas Velocity Dispersion

As already stressed above, the metallicity range of dwarfs must be consistent with the gas energy budget, if both are predominantly regulated by massive stars. So, it is natural to investigate the relationship between the gas velocity dispersion σ and $X_{\rm O}$ in galaxies. Such a relationship, as obtained from our model, is shown and compared with available data in Fig. 4 for three different values of $\phi = 0, 10, 100$ which result in different M_g^f. This relationship is surprisingly tight, in the sense that dI galaxies with higher metallicity tend to show higher velocity dispersions, at least for the uniformly measured van Zee et al. sample. As said above, there are general reasons to expect

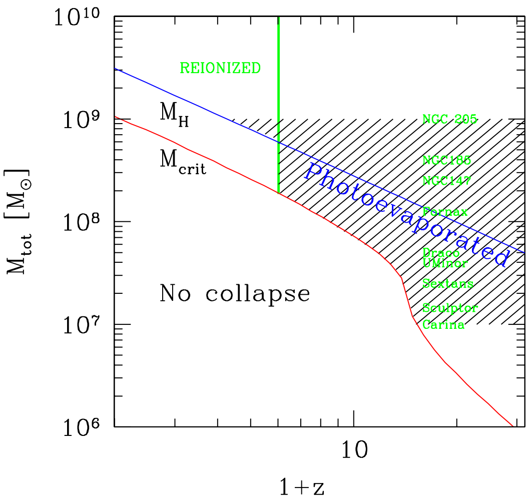

Figure 5: Redshift evolution of the critical mass for collapse, M_{crit}, and for photoevaporation, M_H. The dashed region corresponds to the mass-formation redshift space of objects with total masses in the range of LG dSphs, whose names are listed. Objects with $M < M_H$ can form but they are photoevaporated at reionization (vertical line) or blown away; objects with $M > M_H$ can form even after reionization and survive photoevaporation.

such trend, but the interesting aspect is that all galaxies independently of their DM content fall on the same $X_O - \sigma$ curve, which has the rather steep slope 3.5, as seen from the fitting curve drawn on top of the points in Fig. 4.

Magnetic field effects result in more elastic, and hence less dissipative, cloud collisions. Their inclusion does not modify the above relation between metallicity and gas velocity dispersion, but induces a shift towards larger values. This effect is quantified in Fig. 4 where we have drawn the analogous curves for three different values of b_1, the magnetic reduction factor introduced in eq. 3. A reduction in the cloud collision energy dissipation rate seems to fit better the data, with a preferred value $b_1 \approx 0.5$. This means that about half of the kinetic energy of the clouds is temporarily stored into magnetic line tension and it is released again after the collision, consistent with the findings of Miniati *et al.* (1999).

4 Cosmological Implications

According to standard hierarchical models of structure formation, the star formation activity in the universe started with the formation of the so-called Pop III objects. These are small (total mass $M \approx 10^6 M_\odot$ or baryonic mass $M_b \approx 10^5 M_\odot$) objects characterized by virial temperatures, T_{vir}, below the critical one ($T_H \approx 10^4$ K) at which the cooling necessary for the collapse cannot be provided by hydrogen lines (mostly Lyα line radiation), and molecular hydrogen is then, in a primordial plasma, the only efficient cooling agent. Translating the critical virial temperature into a total mass we obtain $M_H(z) = 4.4 \times 10^9 (1+z)^{-3/2} h^{-1} M_\odot$, where z is the virialization redshift. In order for collapse to take place it is required that the cooling time (whatever species is providing it) is shorter than the Hubble time at the epoch of virialization. This defines a second critical mass, $M_{crit}(z) < M_H$, which has been calculated by Tegmark *et al.* (1997). As a results only objects more massive than M_{crit} can indeed collapse and form luminous objects. The redshift evolution of both M_H and M_{crit} are shown in Fig. 5.

We can now compare these two masses with the ones derived for local dwarfs. The total masses of the best studied dSphs (Mateo *et al.* 1993 present the cases for 9 Local Group dSphs) range from $M_{tot} = 1.1 \times 10^7 M_\odot$ (Carina) up to $M_{tot} = 1.1 \times 10^9 M_\odot$ (NGC205). According to the previous definition $T_{vir} < T_H$, some of them can be classified as Pop IIIs, whereas the more massive ones probably belong to the class of objects able to cool via Lyα. Clearly, as M_H is redshift dependent, the classification depends on the formation epoch. The majority of Pop III objects would be blown-away and their leftover is a tiny naked stellar cluster without gas (but with DM), which could possibly be incorporated in larger structures. The ones which escape merging could still be seen in the nearby universe, although their expected extremely low luminosity should make their detection very challenging.

The possibility that dEs are remnants of blown away Pop III objects has been proposed by Miralda-Escudé & Rees (1997). The results discussed here have been derived by assuming galaxy properties taken from observations of present day dwarfs. However, the conditions at the formation, as the size, gas density, dark-to-visible mass ratio, of dwarfs' progenitors were probably very different. In particular, the critical mass for blowaway depends on the formation redshift and cosmological model. Specific predictions for the Cold Dark Matter model with $\Omega_1, h = 0.5, \sigma_8 = 0.65$, have been made by Ciardi *et al.* (2000) who found that the critical mass for blowaway is approximately $M_c \approx 1 - 2 \times M_H$. Although some uncertainty remains on the correct value of M_c as a result of the poorly known formation properties of galaxies, it is clear that blowaway is a very likely event in these small objects. Noticeable support for the occurrence of blowaway has been brought by an interesting approach recently developed by Hirashita *et al.* (1998). These authors noted that a discontinuity is seen in the dependence of the virial mass/luminosity ratio (analogous to our ϕ parameter) on the virial mass in a sample of local dSph at $M \approx 10^8 M_\odot$. They interpret this discontinuity as produced by blowaway, as low mass objects having lost most of their baryons would be characterized by high values of M_{vir}/L.

In addition to blowaway, other processes may be able to sweep away the galaxy ISM. Photoionization, either produced by external or internal sources, might have an important impact on the evolution of dwarfs. If a UV background (UVB), produced by QSOs and galaxies, is present it might even suppress the formation of dwarfs. The common physical process on which these two ideas are based is that as the gas is photoionized, it is also heated to a temperature that exceeds the virial temperature of the halo itself and cannot be confined by the galaxy gravitational potential. The photoionization temperature of a moderately dense gas is, for a large range of properties of the radiation field and medium density, $T \approx 10^4$ K. Thus, the critical mass relative to photoionization effects essentially coincides with M_H: of course, this is not surprising as both temperatures are regulated by Lyα line cooling, which is an excellent thermostat.

Hence, dSphs must form before a consistent UVB is present in order to be able to accrete the gas, *i.e.* before reionization; subsequently they can lose it when the UVB intensity has increased. In Fig. 5 the obliquely shaded region shows the mass-redshift parameter space were the formation of luminous objects regulated by the processes described above is allowed. The mass bounds of the shaded region are determined by the upper and lower mass limits of the 9 dSphs of the Mateo *et al.* (1993) sample, whose total mass values are superimposed (clearly, we do not know the virialization redshift of these objects). The first conclusion that we can draw from the Figure is that objects like Carina, Sculptor, Sextans, UMinor, and Draco are indeed Pop III objects which must have formed before $z \approx 15$ due to their low masses. Then at reionization, for which we have assumed the conservative lower redshift limit $z_i = 5$, they must have lost their gas either by photoevaporation or blowaway. An exception is represented by Sculptor in which a limited amount of H I ($M_{\rm HI} \gtrsim 3 \times 10^4 M_\odot$) has been detected (Carignan *et al.* 1998). This gas is located at the edge of the galaxy optical image and its association with the galaxy is not completely clear. This gas could have been either part of a self-shielded and hence neutral intergalactic clump, or accreted recently thanks to the drop in the UV background, or IGM pressure confined ejected gas. Larger objects (Fornax, NGC147) could have formed at redshifts much closer that the reionization one and photoevaporated shortly after. NGC 185 and NGC 205 are instead consistently found to have some gas (Young & Lo 1997). This interpretation still has to face the question why dIs with total masses similar to dSphs yet are gas rich. If they have lost their gas in the past, they must have reaccreted material relatively recently when the UVB intensity dropped. Environmental effects might play a role here, as we must require that dIs populate regions where gas accretion is more easily achieved than in those where dSphs of the same mass are found.

Whatever process (blowaway/photoionization) is setting the mass value M_c for gas ejection, might this fact be responsible for the separation between late type and early type dwarfs ? In other words, is it possible that these two galaxy types had common progenitors in the past but they evolved along different evolutionary paths determined by their mass and hence by their ability to retain their gas ? This is certainly an intriguing possibility which would solve the problems caused by a dI $\rightarrow$ dE transition occurring later on. If, as in the latter case, the transition has to be catalyzed by an intense stellar activity expelling the gas, then we should look at BCDs as objects on the point of being transformed into dEs. There are several, apparently insurmountable, difficulties associated with this interpretation, which can be briefly summarized as follows: although BCDs have clear similarities with dIs, however they have *(i)* higher surface brightness, *(ii)* larger radii with respect to dIs (Patterson & Thuan 1996); in addition, van Zee *et al.* (1997a,b) point out that BCDs have higher central mass concentration in both gas and stellar content. Even the second step of the dI $\rightarrow$ BCD $\rightarrow$ dE chain is problematic: the rotation curves of dIs are noticeably different from the ones of both dEs and BCDs, their kinematics being dominated by chaotic motions (Ferguson & Bingeli 1994). The alternative scenario proposed here, in which dI $\rightarrow$ dE transitions do not occur but these objects, starting from the same progenitors, have followed different evolutionary tracks, does not suffer from the above problems. In our view, BCDs would be simply represent a "normal" tail of the distribution of dwarfs massive enough to escape both blowaway/photoevaporation, in addition characterized by higher central mass density which favors the onset of occasional starbursts.

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