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Are interactions the primary triggers of star formation in dwarf galaxies?

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ABSTRACT

We investigate the assumption that the trigger of star formation in dwarf galaxies is interactions with other galaxies, in the context of a search for a 'primary' trigger of a first generation of stars. This is cosmologically relevant because the galaxy formation process consists not only of the accumulation of gas in a gravitational potential well but also of the triggering of star formation in this gas mass, and also because some high-z potentially primeval galaxy blocks look like nearby star-forming dwarf galaxies. We review theoretical ideas proposed to account for the tidal interaction triggering mechanism and present a series of observational tests of this assumption using published data. We also show results of a search in the vicinity of a composite sample of 96 dwarf late-type galaxies for interaction candidates showing star formation. The small number of possible perturbing galaxies identified in the neighbourhood of our sample galaxies, along with similar findings from other studies, supports the view that tidal interactions may not be relevant as primary triggers of star formation. We conclude that interactions between galaxies may explain some forms of star formation triggering, perhaps in central regions of large galaxies, but they do not seem to be significant for dwarf galaxies and, by inference, for first-time galaxies forming at high redshifts. Intuitive reasoning, based on an analogy with stellar dynamics, shows that conditions for primary star formation triggering may occur in gas masses oscillating in a dark-matter gravitational potential. We propose this mechanism as a plausible primary trigger scenario, which would be worth investigating theoretically.

Key words: stars: formation – galaxies: dwarf – galaxies: interactions.

1 INTRODUCTION

Many galaxies show detectable star formation (SF) events. These can have different levels of intensities, from very strong SF events called 'starbursts' to minor, almost indistinguishable SF processes, and can occur either in the centres of galaxies or in their outer regions. At the high end of the intensity scale one finds ultraluminous infrared-emitting galaxies (ULIRGs; Soifer et al. 1987), probably giant and strongly interacting galactic systems. Most of the radiation emitted by the newly formed stars is re-emitted as infrared radiation, because their interstellar matter (ISM) is loaded with high quantities of dust. The SF taking place in ULIRGs is located primarily in their central regions. Another type of star-forming galaxies look almost like stars but show copious SF; these are the compact SF objects.

At the faint end of the SF scale one finds low-surface-brightness (LSB) dwarf irregular galaxies (DIGs). In these systems the SF is not nuclear or systemic, but one finds small SF regions scattered over the galaxy's surface (Heller et al. 1999b). In between these extremes, one encounters various levels of SF in most late-type galaxies.

The nature of SF triggering in galaxies has been studied by many and a plethora of mechanisms have been proposed. In many types of galaxies, more than one mechanism probably operates. In large, well-organized discs there are global SF triggers, such as density waves and shear forces produced by differential rotation. These do not operate in DIGs, which rotate mostly as solid bodies or are supported by turbulent motions, and are generally devoid of spiral structure. The reduction in the number of possible SF triggers implies that DIGs are good subjects in which to study the SF phenomenon in a simple environment.

The more intense the SF, and the longer an SF episode lasts, the more metals are produced in a galaxy. One, therefore, hopes to understand the process of galaxy formation at high redshifts by studying it in nearby, metal-poor dwarf galaxies. The three extragalactic objects with the lowest known metallicity are all dwarf galaxies (I Zw 18, SBS 0335–052, and SBS 0822+3542) and were proposed at times as 'first-time galaxies'. However, the analysis of the underlying stellar population of I Zw 18 (Aloisi, Tosi & Greggio 1999) indicates that this is not a first-time galaxy, despite its paucity of metals. I Zw 18 has probably been forming stars at a slow and steady rate over at least one Gyr.

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We investigated SF and stellar populations in two samples of DIGs in the Virgo cluster (Almoznino & Brosch 1998; Heller et al. 1999b). We showed that the high-surface-brightness DIGs of the 'blue compact dwarf' (BCD) flavour can be understood as originating from a number of starburst events. Each such starburst episode is relatively short, lasts only a few Myr, and the episodes are separated by a few hundred Myr up to a few Gyr. We are currently investigating in a similar manner samples of SF galaxies in voids.

We studied the morphology of star formation in DIGs, hoping that the distribution of H II regions identified as loci of recent SF may pinpoint the proper SF triggering mechanism. The connection between the asymmetry of a galaxy and its star formation properties has already been established by, e.g. Conselice, Bershady & Jangren (2000), but not for a sample of DIGs. We showed that the SF in DIGs is asymmetric and takes place preferentially far from the galaxy's centre, more to one side of a galaxy (Brosch et al. 1998). We also showed (Heller et al. 2000) that this pattern of SF is present not only in Virgo DIGs, but also in other samples of BCD and LSB dwarfs, and that it is reflected not only in the properties of the number counts of H II regions, but also in the distribution of the Hα flux over the galaxy. Therefore, the asymmetry and off-centre SF results are not biased by the small-number statistics of H II regions (Poisson asymmetry). The validation of these results for objects outside the Virgo cluster demonstrates that the cluster environment is not responsible for the asymmetric SF property of DIGs, in line with our preliminary conclusion about the lack of dependence of the Hα equivalent width in Virgo DIGs on the galaxies' (projected) Virgocentric distance (Heller et al. 1999a). Similar results, on the location of sites of recent SF in 10 nearby DIGs, have been reported by Schulte-Ladbeck & Hopp (1998).

Here we concentrate on the possibility that star formation in dwarf irregular galaxies or blue compact galaxies (BCG) is triggered by tidal interactions with other nearby galaxies. We do this mainly by searching for star-forming companion galaxies in a large composite sample of DIGs, all imaged in Hα. The lack of such companions for most of the sample galaxies, along with other supporting evidence, indicates that this mechanism of star formation triggering by external interactions can also probably be discounted as a primary SF trigger. A primary trigger, in our case, is understood to be one that does not require any of the previously mentioned factors in order to become active. Such a trigger could operate in isolated blue compact galaxies, where even a tidal interaction with another dwarf galaxy is probably not sufficient to trigger a SF event (cf. Kunth & Östlin 2000). Note also that our negative results could, in principle, also indicate that the SF in our sample galaxies is entirely secondary, i.e. triggered by internal sources.

We emphasize that the search here is for plausible primary SF triggers that could initiate a first generation of stars in a galaxy. Some of the DIGs we study are good candidates for 'first-time' galaxies. Once some massive stars have formed in a first SF burst, their subsequent evolution produces strong stellar winds and supernova shocks. These may trigger secondary SF, as assumed in the stochastic self-propagating star formation mechanism (Gerola & Seiden 1978). Stewart (1998) showed that this secondary SF mechanism operates in the dwarf galaxies Ho II, IC 2574, and Sextans A. However, searches for primary SF triggers have, so far, been unsuccessful (e.g. van Dyk et al. 1998, for Sextans A).

The plan of this paper is to present in Section 2 published claims that interactions trigger SF, then to explain in Section 3 one of the proposed mechanisms by which SF could be triggered by long-range interactions, and to examine in Section 4 the new observational evidence, which is mainly against this possibility. The discussion in Section 5 will focus on this negative evidence and a scenario will be proposed by which primary SF could be internally triggered.

2 CLAIMS THAT INTERACTIONS TRIGGER STAR FORMATION

The field of galaxy formation and evolution has seen many claims that tidal interactions trigger SF, but very few clear-cut tests of these claims, or detailed theoretical models of such interactions, have ever been presented. We show below that tidal interactions could be responsible for triggering nuclear SF, but they cannot be invoked blindly as a general SF trigger (e.g. Hutchings, Cavanaugh & Bianchi 1999).

Melnick (1987) proposed that collisions between intergalactic gas clouds and dwarf galaxies trigger star formation in the latter. The problem with this assumption is the apparent lack of a significant numbers of intergalactic gas clouds, at least in the form of H I. At about the same time, Noguchi (1987) suggested that interactions between galaxies can drive ISM to the centres of galaxies through the formation of a bar, causing nuclear starbursts to take place. Brinks (1990) suggested that collisions between DIGs may trigger SF. Olson & Kwan (1990a,b) suggested that interactions between galaxies drive ISM cloud–cloud collisions within a galaxy, which may trigger bursts of SF.

Taylor et al. (1995) detected more H I companions around H II galaxies (dwarf irregular galaxies with strong Hα emission) than around quiescent LSB dwarfs; these could be the clouds suggested by Melnick (1987), but they also remarked that a sizeable fraction of the H II galaxies do not appear to have companions at all. Taylor (1997) argued that the excess of companions around H II galaxies may indicate that these are LSBs where SF has been activated by interactions. Telles & Terlevich (1995) showed that there are more bright (non-dwarf) galaxies within 1 Mpc^3 of H II galaxies than expected from a random distribution. Also, Pisano & Wilcots (1999) searched for H I companions around six extremely isolated galaxies from the Nearby Galaxies Catalog (Tully 1988). They found that two of the sample galaxies are really the primary members of triple systems where the H I companions are within 90 kpc of their primary galaxy, but that the other four galaxies appeared isolated in that they did not show H I neighbours.

Moss, Whittle & Pesce (1998) searched for Hα emission in galaxies near the Abell 1367 cluster. They found that objects with compact Hα emission tend to show a disturbed morphology. From this, they concluded that compact line emission, i.e. nuclear star formation, results from tidally induced SF.

Telles & Maddox (2000) searched for faint companions near H II galaxies using automated plate measurement (APM) scans. They concluded that although H II galaxies appear significantly clustered, because of a positive cross-correlation with the APM galaxies, their SF could not be triggered by tidal interactions. The finding of Loveday, Tresse & Maddox (1999) that the majority of local dwarf galaxies undergo star formation at present, and that they are preferentially found in low-density environments, also argues against galaxy interactions playing a role in promoting SF. On the other hand, the disturbed appearance of many high-redshift galaxies (e.g. objects in the *HST* Medium Deep Survey field (MDF) studied by Abraham et al. 1996; galaxies in the *Hubble Deep Field* considered by Conselice & Bershady 1998) has been explained as signs of mergers and interactions.

Iglesias-Páramo & Vilchez (1999) checked for differences in the SF rate between disc galaxies in compact groups and field galaxies. They found that the only characteristic that seems to be different is the width of the distribution of the star formation rate (SFR), which is broader for the compact group sample. This seems to indicate that the dynamic state of a group does not influence the SFR of a galaxy.

Carter et al. (2001) studied the star formation in a large sample of nearby ($z \approx 0.05$) galaxies. They concluded that the presence of star formation in a galaxy is strongly correlated with the neighbourhood galaxy density, defined as the density over a few Mpc. They also found that the stellar birth-rate parameter

$$b = \frac{\mathrm{SFR}}{\langle \mathrm{SFR} \rangle} \tag{1}$$

does not correlate with the local galaxy density, from which they inferred that star formation triggering takes place on a smaller spatial scale than the one defining the Mpc-scale neighbourhood. Similar conclusions were reached by Noeske et al. (2001) from a study of 98 star-forming dwarf galaxies. Specifically, they searched for companions around these galaxies using NED[1] and failed to detect significant differences with distance from the companion in either of two signs of recent SF: the Hβ equivalent width, or the blueness of the $B - V$ colour of the dwarf galaxy.

Schmitt (2001) used galaxies in the Palomar survey with $B_T \leqslant 12.5$ mag in the northern hemisphere to test for the presence of activity (Seyfert, H II, low-ionization nuclear emission region (LINER), etc.) as a function of the local galaxy density or the presence of companions in the NED and the Digitized Sky Survey (DSS). He found, contrary to previous studies, that Seyfert and H II galaxies tend to have fewer companions than other types of galaxies.

An imaging Fabry–Perot study of a small sample of blue compact galaxies by Östlin et al. (2001) indicated that star formation there is likely to be triggered by mergers with gas-rich dwarf galaxies or by massive gas clouds. Severgnini & Saracco (1999) argued that in the Hickson compact groups the correlation between the Hα luminosity of galaxies on the one hand, and the velocity dispersion of a group and its compactness on the other, implies that SF takes place where there is a higher probability of galaxy interaction (lower velocity dispersion for the group).

Pustilnik et al. (2001a) studied the environment of a sample of 86 compact emission-line galaxies and found that about one-third are companions of significantly brighter galaxies. Approximately another third have companions of similar brightness or fainter, and about 15 per cent show indications of previous mergers. From this, they concluded that SF bursts are triggered by interactions with other galaxies.

In more detailed work based on the same galaxy sample, Pustilnik et al. (2001b) separated their sample into one subsample that belongs to the 'Local Supercluster' and one that represents the 'general field' and found small but insignificant differences between galaxies in the two environments in the aspect of the presence of bright disturbing galaxies. Among the galaxies lacking bright disturbers, 'isolated' as per Pustilnik et al. (2001b), 43 per cent are claimed to have dwarf disturbers and 26 per cent to show a merger morphology. These claims will be examined again below. Note that Pustilnik et al. (in their various papers) use an SF triggering mechanism that could activate the process through 'soft' long-range interactions proposed by Icke (1985); this mechanism and its relevance to dwarf galaxies will be discussed below.

Barton Gillespie et al. (2003) studied the SF properties of 190 galaxies in pairs or in compact groups. Their sample represents nearby bright objects ($m_{\mathrm{Zw}} \leqslant 15.5$; $v \leqslant 2300$ km s^{-1}) and the galaxies are relatively close to each other (projected distance $\Delta D \leqslant 50\ h^{-1}$ kpc; $\Delta v \leqslant 1000$ km s^{-1}). They found a clear indication for interaction-triggered SF, with the strongest SF bursts occurring in galaxies in the tightest orbits. Barton Gillespie et al. also found that low-mass galaxies experience stronger SF bursts than massive galaxies.

Finally, Hoffman et al. (2003) studied the H I content of a small sample of Virgo cluster BCDs with Arecibo and VLA D-array mapping. These galaxies show, by definition, strong on-going SF bursts. Their H I maps showed that in about one-third of the galaxies no signs were found for companion galaxies or for gas clouds that may have triggered the observed SF event.

In principle, another type of interaction could also act to trigger SF. This is a tidal triggering by the cluster gravitational potential in which one of the scenarios (Henriksen & Byrd 1996) produces a significant lateral compression of a galaxy disc. This causes enhanced cloud–cloud collisions in the disc, followed by SF, but can happen only for rather close passages near the cluster centre (within 250 kpc) and immediately following the passage (within a quarter of a disc rotation period). This mechanism should, therefore, only enhance SF for galaxy discs near a cluster centre. A similar conclusion was reached by Fujita (1998), while Gnedin (2003) showed that dwarf spheroidal (dSph) and LSB galaxies are unlikely to survive cluster tides. Observationally, the survey by Moss & Whittle (2000) showed that, at least for spiral galaxies, the tidal interactions cause mainly circumnuclear SF, not the diffuse type of starbursts encountered in some dwarf galaxies. For these reasons we believe that the trigger from cluster tides can be discounted for the case of dwarf galaxies.

The conclusion from the evidence summarized above is that the situation regarding SF triggering by interactions is, at best, confusing. There seems to be no clear-cut case of tidal triggering of star formation as a general phenomenon. In many cases, the triggering body that should have had a close encounter with the star-forming galaxy seems to be missing.

3 THE ICKE STAR FORMATION TRIGGER MECHANISM

Could it be possible that SF may be triggered by distant encounters with other galaxies, so that we may not recognize such an event because the galaxies involved are too far apart at present? Following the formalism of Icke (1985), SF could be induced in a DIG by an interaction with another small galaxy, as suggested by Brinks (1990). Icke considered distant encounters between disc galaxies as possible triggers of SF and as a possible explanation for the existence of S0 spirals. His proposal is based on relatively simple numerical hydrodynamic calculations of a gas disc perturbed by an intruder galaxy passing by on a hyperbolic planar orbit. Icke showed that, in some instances, shocks may be generated in the disc even in situations when tidal bridges or tails do not form.

Briefly, Icke's (1985) argument requires a close passage in a prograde sense between the 'victim' galaxy and the 'intruder' galaxy in order to produce shocks in a gas disc. This would speed up the gas by s_0 (the sound speed in the ISM gas) in about half a rotation period of the victim. A supersonic shock is then assumed to trigger SF. The maximal perigalactic distance between the intruder and the

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[1] The NASA/IPAC Extragalactic Data base (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

victim, in order that shocks will take place, must be

$$p_0 \approx \left(\frac{8\pi\mu}{s_0}\right)^{1/3} \tag{2}$$

where μ is the ratio of the intruder mass to the mass of the victim.

Icke's (1985) argument was designed for large spiral discs as victims and large galaxies as intruders, and was aimed at explaining S0 galaxies. Its importance is in providing an apparent way to form stars by galaxy–galaxy interactions that do not leave visible 'traces' in the form of tidal tails or direct collisions. Assuming that this argument holds also for dwarf galaxies, one has only to change the mass ratio and evaluate p_0 in units of r_0, that is, in units of the disc scalelength of the victim DIG. It is possible to use luminosity ratios instead of mass ratios for the two interacting galaxies by assuming some mass-to-light values. If the mass-to-light value is 8 (a somewhat random choice, typical for DIGs and close to the 'maximum disc' value; Gerritsen & de Blok 1999), we find that for a difference of 3 mag between the DIG victim and the large galaxy intruder the perigalactic passage should be closer than $\sim$56 r_0 to trigger an SF shock. A magnitude difference of 6 mag implies $p_0 \leqslant 140\, r_0$ for shocks to be produced.

The implication is that coplanar prograde perigalactic passages closer than 100–200 kpc (for a typical scalelength of 1 kpc for a DIG) should cause 'Icke shocks' that could be responsible for enhanced SF in dwarf galaxies, whereas more distant or out-of-plane passages could not cause such shocks. Note that the delay between the perigalactic passage of a victim to the onset of shock conditions (one half of the victim's rotation as claimed by Icke) does not significantly alter the distance between the galaxies. Larger values of p_0 are feasible for DIGs with $r_0 \gg 1$ kpc, or with $M/L \gg 8$, or with both. It is likely that even if one of these assumptions is fulfilled the victim will not be a typical DIG. For instance, the faint, compact narrow emission-line galaxies studied by Guzmán et al. (1998) at $z \sim 0.22$–0.66 are quite luminous at $M_B \approx -21$, have scalelengths of 1–5 kpc, yet have the masses of dwarf galaxies ($\leqslant 10^{10}$ M$_\odot$).

4 OBSERVATIONAL EVIDENCE

In this section we first review published observations that can be used to test the idea of interaction-triggered star formation, then examine samples of dwarf galaxies studied previously to understand their star-forming properties but concentrating now on finding possible star-forming physical companions.

4.1 Searches for companions in published samples of galaxies

It is possible to test observationally the relation from Icke (1985) adapted to DIGs by considering the sample of dwarf galaxy companions of large galaxies from Zaritsky et al. (1997). The sample consists of 115 satellites of 69 'primary' galaxies, which are closer than 500 kpc (projected) and have a velocity difference from that of the parent galaxy smaller than 500 km s^{-1}. The satellites are at least 2.2 mag fainter than their parent galaxy. The parent galaxies are isolated, in the sense that all companions within 1000 km s^{-1} and 500 kpc projected distance are fainter by more than 2.2 mag, and those within 1000 km s^{-1} and between 0.5 and 1.0 Mpc are at least 0.7 mag fainter than the primary galaxy. The sample is useful, therefore, to study the frequency of SF in the companions as a general property and as a function of their distance from the 'intruder', that is, the primary large galaxy.

Zaritsky et al. (1997) list, for each of the companions, the presence or absence of emission lines in their spectra. Although not specifically mentioned in the paper, it seems that the lines used for establishing the presence or absence of emission were the [O II] doublet, Hβ, and the [O III] lines. We take the presence of emission lines to imply the existence of young, massive stars that signal the presence of a recent SF event in the dwarf companion. The inference, if Icke's (1985) proposed SF trigger mechanism can be applied here, is that the closer a dwarf is seen to its parent galaxy, the 'intruder' in Icke's terminology, the more likely would it be to exhibit emission lines in its spectrum. In particular, by binning the companions into 'close' and 'distant' groups, we expect to observe a marked difference between them in terms of their SF properties.

We counted in the list of Zaritsky et al. (1997) the number of companions with emission lines within 200 kpc projected separation, and the number within 200–400 kpc. We found that exactly 85 per cent of the companions in both cases exhibited emission lines (47 out of 55 for the companions closer than 200 kpc, and 33 out of 39 for those more distant). It seems that the presence of emission lines is a general characteristic of the companions of large galaxies. We conclude that the assumption of tidally induced SF, manifested as the result that the closer subsample would form stars more readily and thus would show a higher fraction of star-forming dwarfs, was not satisfied. This supports the assertion that the Icke (1985) mechanism is probably not relevant as a trigger of SF in dwarf companions of large galaxies where tidal SF triggering could be expected.

On the other hand, Pustilnik et al. (1997) also claimed that many blue compact galaxies (BCGs) have bright, nearby companions. They used objects from the Second Byurakan Survey (SBS) and searched their neighbourhoods for brighter objects with which the BCGs could have interacted. The Pustilnik et al. sample consists of 62 BCGs with v$_\odot \leqslant 6000$ km s^{-1}, from which they selected a subsample of 26 BCGs closer than 2500 km s^{-1}. The possible companions were selected to be brighter by at least 1.4 mag than the target BCG and their radial velocities were checked spectroscopically. The search strategy was, therefore, opposite to that adopted by Zaritsky et al. (1997). Pustilnik et al. searched for companions of the BCGs that are brighter than the BCGs. Objects within 300 km s^{-1} were adopted as companion galaxies, i.e. possible 'intruders', following Icke's classification.

The reported success rate in finding intruders was 15/26 (58 per cent) for the nearby subsample, and 28/62 (45 per cent) for the entire BCG sample. If one assumes Poisson statistics for the likelihood of detection, these percentages are not different and indicate that about half of the galaxies have companions. The mean projected separation of a 'victim' BCG from its brighter, presumably more massive 'intruder' was $\sim$250 kpc, and the mode of the distribution of the magnitude differences between the two objects was $\sim$3 mag. From this, Pustilnik et al. (1997) concluded that SF activity in BCGs is most likely triggered by long-range tidal interactions with large neighbours, following Icke's (1985) proposal. However, it appeared that closer passages do not, necessarily, trigger more intense or more frequent SF (cf. also Carter et al. 2001).

The findings of Pustilnik et al. (1997) contradict, apparently, the evidence from the data of Zaritsky et al. (1997). Note first that the terms BCG and BCD are not interchangeable. The 1.4-mag difference between the victim and the intruder does not ensure that the BCG victim would always be fainter than $M_B \approx -19$ so as to qualify as a dwarf galaxy. It is possible that many BCG sample galaxies of Pustilnik et al. are not dwarf galaxies. It is also likely that the SF they detected in the sample objects is in many cases nuclear, and this could be related to tidal interactions. A hint that this could be the case is that the galaxies are SBS objects, i.e. were detected as compact emission-line objects in an objective-prism survey, while some of them appear extended in wide-band images.

4.2 Star-formation triggering in small galaxies

We assume that if the SF is triggered by an interaction with a neighbouring small galaxy, the trigger should operate not only on the target galaxy but also simultaneously on the disturbing object. Therefore, we assume in what follows that when Hα emission is triggered in the DIG that is the target of the SF study, similar Hα emission appears in (at least) one of the galaxies in the immediate neighbourhood of the target DIG. This assumption may not be fulfilled if the disturbing galaxy has no interstellar gas, and thus cannot form new, massive stars, or if it does not have sufficient ISM to be ionized and be detected as Hα emission, or if the SF time-scales in the two objects are widely different.

We studied a composite sample of 96 DIGs, most of which were used initially to explore the issue of asymmetric and non-central SF in such objects (Heller et al. 2000). The galaxies originate from the Almoznino & Brosch (1998) studies of Virgo BCDs extended to include all the Virgo galaxies classified as BCD or any other morphological class and BCD ($N = 40$; Brosch et al. in preparation), and from the Heller et al. (1999b) study of a complete Virgo LSB DIG sample ($N = 18$). As the original studies required that the galaxies be members of the Virgo cluster (VC), we imposed also the following selection criteria: (a) a positive detection in H I, as listed in Hoffman et al. (1987); Hoffman et al. (1989), and (b) a radial velocity from optical or H I observations smaller than 2600 km s^{-1} to ensure membership in the Virgo cluster. Most galaxies in Heller et al. are classified in NED as ImIV or ImV.

We added galaxies from a private collection of Liese van Zee (LvZ; $N = 18$), and from a similar collection by John Salzer (JS; $N = 20$). These two lists have already been used in our study of SF asymmetry (Heller et al. 2000). Because of this non-uniform selection, the composite sample is not representative or complete in any way; it is used here only as an indicative survey of SF properties among companions of dwarf galaxies. For instance, while most LvZ galaxies are classified in NED as Magellanic irregulars (Im), those of JS are mostly BCDs. The fraction of objects carrying the classification BCD from the entire sample is 64 per cent (61/96).

The galaxies in the composite sample are uniformly classified as dwarf galaxies, of subclasses BCD, LSB or Im of various subtypes. The objects are all relatively nearby, at distances of order that of the Virgo cluster or nearer, with only two objects (UGC 2535 and UM 408) at redshifts higher than 2600 km s^{-1}. They all have net Hα images as well as continuum light images obtained in an off-Hα band or in the *R*-band, but in rare cases only in the *B*-band. The net-Hα images were obtained by subtracting the continuum contribution from the rest-frame Hα image. The red continuum image was scaled to the Hα image by a factor chosen to cause stars to subtract fully from the net image. This procedure is justified, because the Hα line filters used for rest-frame galaxy photometry sample line-free segments of the spectra in most stars.

The net Hα line images were inspected visually for the presence of diffuse objects in the field, not obviously related to the target galaxy (outer H II regions in the galaxy, for example). Note that the images from the LvZ list have had some of the brighter stars and galaxies blocked off in the line image; this could have masked off some Hα contribution eliminating some possible companions. As the Hα filters used in this survey are all rather narrow, any such diffuse image detected in the net-Hα image represents a galactic-shaped object at about the same redshift as the target galaxy. Specifically, the typical filter full width at half maximum (FWHM) of 50 Å implies a maximal redshift difference of ∼2000 km s^{-1} between the target galaxy and a potential companion if the two galaxies are located at the two ends of the transmission band. In reality, the redshift difference must be much smaller in order for a potential companion to be revealed in the net line image, because the transmission profile of the filter would attenuate significantly the intensity of an Hα line originating from an object red- or blue-shifted close to the edge of the filter band and, in most cases, the central wavelength of a filter would be tuned to the target galaxy redshift. The visual inspection is limited to the size of the net Hα image, and the projected size of the search area changes with the distance to the target galaxy.

Note that, unlike other studies of this topic, we do not claim that a disturbed morphological appearance is a clear indicator of an interaction. This criterion might be valid for large, well-behaved galaxies that have regular patterns, but it is not acceptable for dwarf irregular galaxies. The presence of companions was verified by blinking the line and continuum images; real companion galaxies must have counterparts in both images (line and continuum), ruling out the detection of galaxies with very dim continua and strong emission lines. In principle, the non-Hα-emitting galaxies could also be 'intruder' galaxies and may have triggered SF if they are at the right redshift, but this could not be detected with the present technique.

We also conducted a NED search for possible nearby companions, limiting this to a projected distance of 5 arcmin and a Δv of 1000 km s^{-1}. For a typical distance of 20 Mpc to the sample galaxies, this angular distance corresponds to a projected distance of 300 kpc. The companions found this way are listed in the remarks column of Table 1 as 'pair with' (p.w.), followed by the name of the companion and its approximate projected distance in arcmin.

The objects studied in this way are listed in Tables 1–4 . The tables give one of the names of the galaxy in the first column, its morphological type in column 2, its heliocentric velocity and semimajor axis (*a*, in arcmin) in columns 3 and 4, the distance from the galaxy searched for possible Hα companions (A, in galactic radii, using the off-line or continuum image) in column 5, and the number of possible Hα companions identified in column 6. We add other names for the galaxy in column 7 and sometimes we mention one or more possible companions as a pair with the galaxy (p.w. in the table) for which we give the projected distance (see below). The redshift $v_{\odot}$, the size of the semimajor axis *a*, and the morphological type are the values listed in NED or in Hoffman et al. (1987); Hoffman et al. (1989) or in Pustilnik et al. (1995). A few *a* values are major-axis estimates from the images of the galaxies in the DSS. If the name itself is prefixed by an asterisk, we include below a short discussion of this specific object. The different subsamples are separated in the table by horizontal lines.

Tables 1–4 indicate that only one DIG from our sample of 96 objects has an H II companion (VCC 2034, with VCC 2037). To this we can add 12 galaxies with possible companions that do not show Hα emission found through the NED search. A few objects in these tables are worth a few additional comments.

(i) **VCC 0340.** This object is listed as the seventh galaxy in the poor cluster WBL 392 in the catalogue of White et al. (1999), along with 11 other objects. The WBL catalogue lists concentrations of three or more galaxies brighter than $m_{\rm pg} = 15.7$ with a surface overdensity of 21.54 ($10^{4/3}$). The redshift of the proposed poor cluster is derived as the average of the redshifts of the individual galaxies. Given its location and redshift, it is clear that WBL 392 is a galaxy

Table 1. Possible H II companions of dwarf star-forming galaxies: Virgo BCDs.

Name	Type	$v_{\odot}$ (km s^{-1})	a (arcmin)	A (a)	N	Remarks
VCC 0010	BCD:	1971	0.6	2	0	
VCC 0022	BCD?	1691	0.1	60	0	
VCC 0024	BCD	1289	0.5	24	0	
VCC 0130	BCD?	2189	0.3	30	0	
VCC 0135	S pec/BCD	2378	1.0	10	0	
VCC 0144	BCD	2021	0.4	3	0	
VCC 0172	BCD:	2175	0.7	20	0	
VCC 0207	BCD?	2564	0.25	45	0	
VCC 0213	dS?/BCD	–154	0.6	15	0	
VCC 0223	BCD?	2070	0.2	50	0	
VCC 0281	dS0 or BCD	257	0.4	53	0	IC 3120
VCC 0309	Im/BCD	1566	0.6	19	0	
VCC 0324	BCD	1526	0.7	14	0	
VCC 0334	BCD	–254	0.3	70	0	
*VCC 0340	BCD or merger	1512	0.5	18	0	in WBL 392
VCC 0410	BCD	283	0.2	54	0	RMB 12669
VCC 0428	BCD	794	0.4	77	0	p.w. VCC 0413@4′.2 and $\Delta v = 520$ km s^{-1}
VCC 0446	Im/BCD:	825	0.8	11	0	
VCC 0459	BCD	2107	0.4	24	0	
VCC 0468	BCD?	1979	0.3	27	0	
VCC 0513	BCD?	1832	0.4	16	0	
VCC 0562	BCD	44	0.3	3	0	KUG1220+124
VCC 0641	BCD?	906	0.4	15	0	
VCC 0655	S pec, N:/BCD	1146	1.7	11	0	NGC 4344
VCC 0737	Sd/BCD?	1725	1.0	9	0	
VCC 0741	BCD?	1861	0.4	17	0	
VCC 0772	BCD?	1226	0.3	29	0	
VCC 0841	BCD	501	0.4	24	0	RMB 46
VCC 0848	ImIII pec/BCD	1537	1.0	15	0	
VCC 0890	BCD?	1483	0.14	28	0	
VCC 0985	BCD?	1638	0.3	25	0	
VCC 1141	BCD?	1040	0.32	55	0	p.w. VCC 1164@3′.4 and $\Delta v = 0$ km s^{-1}
VCC 1179	ImIII/BCD	764	1.0	15	0	IC 3412
VCC 1313	BCD	1254	0.2	18	0	RMB 132
VCC 1356	SmIII/BCD	1251	0.6	14	0	IC 3446
VCC 1374	ImIII/BCD	2559	1.0	12	0	IC 3453
VCC 1437	BCD	1160	0.3	21	0	
VCC 1459	BCD:	1774	0.4	4	0	p.w. IC 3474@4′.2 and $\Delta v = 47$ km s^{-1}
VCC 1572	BCD	1848	0.5	34	0	
VCC 1725	SmIII/BCD	1067	1.1	10	0	
VCC 1744	BCD	1150	0.36	43	0	p.w. IC 3602@5’ and $\Delta v = 129$ km s^{-1}
VCC 1750	BCD?	−117	0.2	13	0	
VCC 1791	SBmIII/BCD	2088	1.4	9	0	IC 3617
VCC 1804	ImIII/BCD	1898	0.9	35	0	
VCC 1955	S pec/BCD	2012	1.2	10	0	NGC 4641
VCC 2007	ImIII/BCD:	1857	0.4	28	0	IC 3716
VCC 2033	BCD	1486	0.4	51	0	
VCC 2037	ImIII/BCD	1142	1.3	20	0	p.w. VCC 2034@3’ and $\Delta v = 459$ km s^{-1}

condensation within the Virgo cluster, near its southern edge. Table 2 in White et al. lists a few other similar condensations nearby.

(ii) **VCC 0329.** This object is listed as a member in the same poor cluster WBL 392 as VCC 0340. Note that while VCC 0340 is classified as a BCD/merger, VCC 0329 is an LSB dG. The two dwarf galaxies are only 5 arcmin (∼24 kpc, projected) and 110 km s^{-1} apart, yet the first is copiously forming stars while the second is not, although it has significant amounts of H I (approximately one-third of the H I in VCC 0340 and with a similar line width; Hoffman et al. 1987).

(iii) **U10281.** A search of NED in the neighbourhood of this galaxy reveals an apparent companion only 1.5 arcmin away. This is [BH98]16110+1720 listed with a redshift that differs only by 5 km s^{-1} from that of U10281, originating from the study of the Hercules supercluster kinematics by Barmby & Huchra (1998). However, the DSS image of the potential companion displayed by NED shows nothing. It seems that the table listing the galaxies studied by Barmby & Huchra contained some typing mistakes that were not corrected in the erratum to the paper, and were propagated into NED.

(iv) **U9762.** This galaxy has two companions. One is listed in Table 1 here, from a NED search. The two are discussed by Pisano & Wilcots (1999), where the companions were found through an H I imaging survey with the VLA-D. The companion listed in Table 1 is

Table 2. Possible H II companions of dwarf star-forming galaxies: Virgo LSBs.

Name	Type	$v_\odot$ (km s^{-1})	*a* (arcmin)	*A* (a)	*N*	Remarks
VCC 0017	ImIV	826	1.3	3	0	U7150
VCC 0168	dE2 or ImIV	682	0.4	5	0	
VCC 0169	ImV	2222	0.8	3	0	
VCC 0217	ImIV–V:	1184	1.7	2	0	U7307
VCC 0260	ImIV	1775	0.6	5	0	
VCC 0328	ImIV	2179	0.9	15	0	Boe 113
*VCC 0329	ImV?	1622	0.3	10	0	member WBL 392
VCC 0350	ImIV–V:	305	0.6	5	0	
VCC 0367	ImV?	2362	0.3	5	0	p.w. N4270@1′ and $\Delta v = 5$ km s^{-1}
VCC 0381	ImV	481	0.8	4	0	
VCC 0477	ImV	1866	0.9	4	0	
VCC 0530	ImIV–V	1299	1.1	3	0	p.w. IC 0783*A*@4′.9 and $\Delta v = 92$ km s^{-1}
VCC 0565	ImIV	877	0.5	7	0	
VCC 0584	ImIV–V	56	0.6	4	0	p.w. VCC 0571@2′.9 and $\Delta v = 991$ km s^{-1}
VCC 0628	ImV:	−398	0.3	12	0	
VCC 0826	ImIV	1505	1.3	3	0	
VCC 0963	Im:	1866	0.4	2	0	
VCC 1448	ImIV or dE1 pec	2583	1.7	3	0	
VCC 1455	ImIV	1340	0.6	5	0	
VCC 1468	ImIV	1233	0.9	4	0	
VCC 1585	ImIII–IV pec	668	1.5	3	0	IC 3522
VCC 1753	ImIV	737	0.6	5	0	
VCC 1784	ImV	57	0.7	5	0	
VCC 1816	ImIV–V	1006	1.0	7	0	
VCC 1822	ImIV	1012	0.6	10	0	
VCC 1952	ImIV	1308	0.6	7	0	
VCC 1992	ImIV	1010	1.1	4	0	U7906
VCC 2034	ImIV	1500	0.8	10	1	p.w. VCC 2037@3′ and $\Delta v = 459$ km s^{-1}

a compact dwarf galaxy with an extended H I envelope and with Hα emission. The other (northern) companion is an LSB object with 7.1×10^8 M$_\odot$ of H I and a dynamical mass (cf. Pisano & Wilcots) higher than 10^{10} M$_\odot$.

(v) **UM 439.** NED carries a note about this object regarding the presence of a possible H I companion. This is the result of interpreting the disturbed and asymmetric H I profile measured by Taylor et al. (1995). However, a later modification of this NED note by C. Taylor, mentioned also in the original paper, indicates that the disturbance could be the result of a tidal interaction, even though the disturber was not readily identified. The contours in their fig. 4 show that the H I distribution is centred on the optical galaxy; the east–west distortion and the H I peak at 1110 km s^{-1} and 1.5 arcmin north-west of the optical galaxy could represent the companion, though no optical counterpart is readily discernable.

5 DISCUSSION

We showed above that samples of dwarf, star-forming galaxies do not show the presence of significant numbers of companions that have contemporaneous star formation with the target galaxy. Although the survey is not uniform and does not cover equal areas around each galaxy, our composite look searches for neighbours in a range of distances, both in the immediate neighbourhood (up to five galactic radii for half of the sample) and to within 20 radii or more for about one-quarter of the galaxies. The results for our sample of 96 galaxies are indicative, but do not represent any complete sample. To summarize, we found that one dwarf galaxy has a possible Hα companion and, through NED searches, identified 12 other cases of possible companions that do not show Hα emission. In comparison, the majority of companions of large galaxies in the Zaritsky et al. sample do show line emission.

The lack of detected Hα companions shows that the tidally induced SF trigger is probably not operating in DIGs, or is not important in such galaxies, some of which may be, as already mentioned, ‘first-time’ galaxies. This conclusion confirms previous similar statements (e.g. Mihos et al. 1997; Telles & Maddox 1999; Telles & Melnick 1999). We also showed that the cluster tides are probably not relevant to the question addressed here.

In fact, we can provide some counterexamples where one would expect a strong tidal interaction from a massive companion, and the dwarf galaxy has considerable amounts of H I, yet no visible star formation is detected. One such case is VCC 0367, an LSB dIrr (Im V) that is only 1 arcmin and 5 km s^{-1} away from the large S0 galaxy NGC 4270. VCC 0367 has considerable amounts of H I; 0.59 Jy km s^{-1} (Huchtmeier & Richter 1989) and the 21-cm line is fairly wide ($w_{50} = 98 \pm 10$ km s^{-1}; Bottinelli et al. 1990). The lack of any signs of interaction in this case, when one would expect a strong tide to act between galaxies that are so close to each other, indicates presumably a failure of the basic assumption that a small angular distance coupled with a negligible redshift difference implies necessarily that the two objects are equidistant from us. Presumably one of the two galaxies is located at a large distance from the other and has a strong peculiar velocity that mimics the redshift of the other.

We are left in a somewhat difficult position in any attempt to explain the pattern of SF we observe in DIGs. To recapitulate, we showed that both high-surface-brightness (BCD) as well as LSB DIGs exhibit SF. The star formation takes place mostly at the outer boundaries of a DIG and not at its centre (except for some BCDs).

Table 3. Possible H II companions of dwarf star-forming galaxies: van Zee sample.

Name	Type	$v_{\odot}$	*a*	*A*	*N*	Remarks
DDO210	IB(s)m	−137	2.2	2	0	
HARO43	BCD?	1912	0.5	12	0	
*U10281	Im:	1080	1.8	5	0	p.w. BH16110 + 1720@1′.5 and $\Delta v = 5$ km s^{-1}
U1175	Sm:	728	1.1	10	0	
U11820	Sm:	1104	2.0	2	0	
U191	Sm	1144	1.6	5	0	
U2162	IB(s)m	1185	1.5	6	0	
U2535	Im:	2968	0.9	21	0	
U2684	Im?	350	1.8	4	0	
U2984	SBdm:	1543	1.7	4	0	p.w. NPM1G +13.0146@4’ and $\Delta v = 10$ km s^{-1}
U300	Im:	1346	1.3	5	0	
U3050	S?	2147	0.9	15	0	
U3174	IAB(s)m:	670	1.7	2	0	
U3672	Im	994	1.2	5	0	
U4660	Sm:	2203	1.2	4	0	
U4762	Im	2026	1.0	12	0	
U521	Im	659	0.9	11	0	
U5716	Sm:	1277	1.3	2	0	
U5764	IB(s)m:	586	2.0	7	0	
U5829	Im	629	4.7	1	0	VV 794
U634	SABm:	2216	1.7	4	0	
U7178	IAB(rs)m:	1339	1.4	4	0	
U7300	Im	1210	1.4	6	0	
U8024	IB(s)m IV–V	376	3.0	4	0	
U891	SABm:	643	2.3	2	0	
U9128	ImIV–V	154	1.7	5	0	
*U9762	Sm:	2273	1.0	4	0	p.w. 2MASXi J1511566 + 323553@4′.2 and $\Delta v = 43$ km s^{-1}
UA357	Im	1170	0.8	2	0	

Table 4. Possible H II companions of dwarf star-forming galaxies: Salzer sample.

Name	Type	$v_{\odot}$	*a*	*A*	*N*	Remarks
IIZw40	BCD; Sbc; merger H II	789	0.6	2	0	UGCA 116
IZw18	BCD	745	0.2	13	0	
GR8	ImV	214	1.1	6	0	
Leo A	IBm:	20	5.1	2	0	
Mk324	BCD	1600	0.3	12	0	
Mk328	BCD/E	1379	0.3	7	0	UGCA 441
Mk36	BCD	646	0.3	7	0	UGCA 225
Mk475	BCD	540	0.2	11	0	
Mk5	I?	792	0.7	5	0	
Mk600	SBb; BCD	1008	0.4	11	0	
Mk750	BCD	754	0.4	6	0	
Mk900	BCD/E	1146	0.8	9	0	
UM133	H II	2098	1.0	5	0	
UM323	BCD?	1799	0.5	7	0	
UM408	H II	3598	0.2	23	0	
UM40	SB0?	1344	0.6	5	0	
*UM439	compact	1122	2.0	13	0	UGC 6578; H I companion?@1’ and $\Delta v = 27$ km s^{-1}
UM461	BCD/Irr; H II	1007	0.4	11	0	
UM462	H II	1051	0.6	7	0	UGC 6850; two H I companions@0′.1 and $\Delta v = 144$, 155 km s^{-1}
WAS 5	BCD; H II	1259	0.2	16	0	

It also tends to concentrate more to one side of a galaxy, rather than being distributed with equal probability over the galaxy. Unless we assume that near each such galaxy there is a dark-matter halo lacking H I and luminous stars, which provides the tidal force to trigger the SF, we are compelled to abandon an attempt to explain SF initiation by interactions.

The lack of external SF triggers implies that, in any explanation, we must turn to internal phenomena to trigger the process, but as we already mentioned in the introduction, large-scale internal triggers that could be relied upon to produce asymmetry (such as density waves or a bar instability) are absent in DIGs. In this context, we note that Hunter (1997) already concluded that SF is largely a regional process and that in irregular galaxies it is probably regulated by a combination of processes such as gravitational instabilities, thermal pressure of gas in a disc, and modification of the ISM by massive stars, as well as random gas motions.

Lacking a plausible trigger for the SF process, we propose here a new possibility, which is at this stage only a scenario, not a full-power model. We call this the 'churning bag' idea, which, simply put, assumes that SF takes place when a mass of gas is sloshing around within the dark-matter halo of a dwarf galaxy. The gas could find loci of standing waves probably at the turn-around points, where the gas may be compressed and could reach SF conditions. As this is a three-dimensional problem in a possibly non-spherical (even triaxial) potential, many suitable locations may exist in a dark-matter halo. These may appear randomly distributed over the face of a galaxy, but will tend to occur preferentially near the edges of the gas mass, and there it would be more likely to find locations that could form stars. This could explain the finding of off-centre star formation in DIGs (cf. Brosch et al. 1998; Heller et al. 2000).

The question of gas oscillations in the gravitational potential of a galaxy with subsequent star formation has been studied by Nelson (1976) in the context of searching for a mechanism to explain the 'corrugations' observed in the Galactic disc, and by de Zeeuw (1984) in the context of the gas fate in a triaxial gravitational potential. A related phenomenon, external shells in elliptical galaxies, has been studied by Quinn (1984) and by Hernquist & Quinn (1987).

The problems of galactic-scale oscillations are similar, because the observed peculiarities arise when the 'tracer' material, be it either gas or stars, adjusts itself to an external gravitational potential. The difference is that gas is much more dissipative than stars. In the case of shell galaxies, the observed features are produced by the accretion of a low-mass companion galaxy. The external shells are explained as being the result of stars from the accreted object sloshing in the gravitational potential of the elliptical galaxy. Each shell forms at the turning points of the accreted stars. The simulations deal mostly with the fate of stellar systems as the accreted companions.

Weil & Hernquist (1993) studied merger simulations of systems consisting of gas and stars. The difference, with respect to previous calculations, is the rapid separation of the gas from the stars, with the gas settling in compact discs or rings near the central region of the accretor galaxy at the bottom of the gravitational potential. The stars form essentially a collisionless fluid affected on longer time-scales by dynamical friction. One example presented by Weil & Hernquist in this context is NGC 2685, the Spindle galaxy, an object showing traces of at least two accretion/merger events. The more recent one resulted in a luminous ring along the minor axis of the galaxy, in which SF takes place at present (Eskridge & Pogge 1997). Hα images of NGC 2685 show compact H II regions within the ring; these are rather similar to the H II regions we observe in the DIGs we studied and, as mentioned above, this star formation process does take place in the outer regions of NGC 2685.

An oscillatory behaviour of the star formation process, induced by a mass-exchange process between the disc and the halo of a galaxy, has been studied by Korchagin, Ryabtsev & Vorobyov (1994). This, as noted also by Hirashita, Burkert & Takeuchi (2001), could explain the intermittent SF history of many galaxies including our own. Note, though, that the 'oscillatory' description relates in this case to the rate of SF in a certain location, not to the spatial shifting of the SF regions within a galaxy.

Sloshing, in the context of a galaxy–galaxy interaction, was studied by Zeltwanger, Comins & Lovelace (2000). They simulated the rapid parabolic passage of a companion next to a target disc galaxy and found that this could bring the centre of mass (CoM) of the disc to an offset position. The offset CoM would subsequently decay and this would create a transient, one-armed spiral pattern. Given that this is a 2D N-body simulation that does not include gas, we would expect a more dramatic behaviour from a gassy disc.

The sloshing of a stellar cluster within the halo of the dwarf spheroidal galaxy in Ursa Minor was described by Kleyna et al. (2003). They analysed stellar radial velocities in this nearby galaxy and found two kinematically separated stellar populations. This demonstrates that decoupled structures can survive for long periods, a number of Gyr, in the halo of a dwarf galaxy. In the case of a dissipative mass of gas it is likely that the lifetime of such an entity would be rather short, but presumably sufficient to trigger a SF event near the edge of the galaxy at the turn-around location.

We have established above that a sloshing mode of motion can take place in a galaxy, and now propose a scenario for the sloshing mode of star formation. We emphasize again that this description is not based on a model calculation. Imagine a mass of gas recently collected by a small dark-matter halo, similar to those thought to exist around DIGs. The gas could originate from a recent accretion event, or could be a concentrated blob ejected from the galaxy itself and reaccreted by it. Before the gas fully relaxes to a disc it is likely to oscillate within the gravitational potential of the halo. These oscillations would mostly tend to be radial and when a gas mass reaches its apogalactic point it will reside there longer than in regions closer to the centre of the potential. Moreover, the central regions will have an approximately flat gravitational potential profile, and thus will not be conducive to much mass concentration. Adding to this the lower cooling efficiency of metal-poor gas, which would reduce the SFR to less than one-third of that in metal-rich gas (cf. Gerritsen & de Blok 1999), implies that the outer regions of the galaxy will tend to form stars more efficiently than other locations in it, as indeed our studies have found. This star formation process would then be similar to the SF trigger discussed by Elmegreen (1998) as the 'collect and collapse' mode, in which the gas accumulates in a dense ridge that collapses gravitationally into dense cores.

Note that we did not discuss here how the gas became trapped in the dark-matter halo. This may be the result of slow cooling of gas in the halo of the protogalaxy (cooling flow), or gas could be accreted from intergalactic space, or it could even be torn off another protogalaxy. As already mentioned above, this could even be gas ejected from the galaxy and now on an infalling trajectory. The presence of gas is an a priori requirement for recent star formation, and there might be conditions where it could begin to form stars without external influences; this is the main point of the present paper.

6 CONCLUSIONS

We analysed published samples of galaxies with companions and showed that there does not seem to be a strong link between the distance from a companion to the parent galaxy and the strength of the starburst detected in a galaxy. We also demonstrated that in a composite sample of dwarf star-forming galaxies there are few star-forming companion galaxies. These findings support the view that galaxy–galaxy tidal interactions, particularly the long-range encounters proposed by Icke (1985) as one of the possible star formation triggers, are not very much involved in activating the SF process in dwarf galaxies. It is possible that some internal triggers, such as the sloshing of gas in a dark-matter halo followed by apogalactic gas accumulation at the turn-around locations, provide such primary triggers of SF. This could be the case for some of the star-forming and apparently isolated galaxies, such as those in our sample. In other objects, the SF could be secondary, triggered by supernovae, stellar winds, etc. Whether this is indeed the case could be revealed by detailed studies of the star formation history of these objects.

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