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Morphological aspects of star formation in dwarf galaxies

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Abstract.
We studied the morphology of star formation in dwarf irregular galaxies and found that, in general, this takes place on one side of a galaxy and far from the center. This is mainly true for low surface brightness galaxies; in high surface brightness dwarf irregulars the star formation tends to be more centrally concentrated, as well as being more intense. We discuss possible star formation triggers in dwarf irregular galaxies, and evaluate the reasons for the peculiar distribution of star forming regions of these galaxies. Stochastic star formation, interactions with external gas, and tidal interactions appear to be ruled out as responsible for the asymmetric pattern of star formation. We conclude that asymmetry of a dark matter halo or of an asymmetric underlying stellar distribution may trigger an asymmetric pattern of star formation.

Keywords: star formation, dwarf galaxies, HII regions, morphology

1. Introduction

What triggers the star formation in galaxies ? How does it proceed once triggered ? Although much has been written on these subjects they are by no means much clearer today than they were two or three decades ago, when the field of galaxy evolution was just beginning to emerge as a branch of astrophysics.

In principle, the star formation (SF) can be characterized by two boundary condition parameters: the initial mass function (IMF) and the star formation rate (SFR). The IMF was originally described by Salpeter (1955) as a power law. It describes the number of stars formed per unit stellar mass and the exponent in the Salpeter formulation is −2.35. A number of possible modifications of the IMF have been proposed over the years; we shall not review these in detail. It suffices to mention modifications by Miller & Scalo (1979), Kennicutt (1983), and Scalo (1986), some of which may be represented as piecewise power laws. Parenthetically, we also mention the possibility of a metallicity dependence of the IMF (*e.g.*, Terlevich & Melnick 1983).

The SFR has been proposed to be a power law of the gas density (Schmidt 1959), but other formulations have also been put up. Some other possibilities were a dependence on the gas **surface** density, or on this density combined with a dynamical parameter (*e.g.*, Silk 1997). However, these relations may not always represent the most significant dependencies. For instance, in a sample of

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spiral galaxies the SFR, as measured by the strength of the Hα emission, was found to correlate with the blue surface brightness (Phillipps & Disney 1985). A similar correlation with starlight for a dwarf galaxy sample was found by Hunter *et al.* (1998).

There have also been numerous suggestions of possible SF triggers. For example, Larson (1986) proposed that large scale gravitational instabilities, cloud compression by spiral density waves, compression by shear forces in a rotating disk, and random cloud collisions in the ISM are the major SF triggers. To these one may add shock waves from stellar winds and SNe, tidal interactions, collisions with other galaxies, ISM stripping, and cooling flow accretion in specific galaxies. SF triggering mechanisms were reviewed by Elmegreen (1998).

Because of the proliferation of potential SF triggers, it is difficult to understand the process in large, well-established galaxies. For this reason we decided to concentrate our efforts in studying SF among the dwarf galaxies (DGs). These are devoid of differentially-rotating disks, thus the shear forces which act in such disks will not be counted among potential trigger mechanisms for DGs. In addition, dwarf irregular galaxies can hardly be classified as "spirals", thus an additional potential trigger may be ruled out: the density waves.

By careful selection of the sample galaxies one may probably discount tidal triggering of SF if the objects are selected to be far from other galaxies. One caveat related to this issue is the possibility of delayed star formation, following a soft (distant) tidal encounter, if this somehow triggers a rain of gas clouds onto the disk (Vázquez & Scalo 1989). Another option is to select the sample from a well-defined galaxy environment, where tidal triggering should average out among the galaxies of the sample. Selection within a cluster of galaxies would conform to this requirement but would not yield many dwarf irregulars with star formation, as these tend to avoid high galaxy density environments.

We selected our initial sample of galaxies from the Virgo cluster. The advantage is that the environment is well-defined, the objects are (relatively) nearby, and the Virgo sky region is accessible from both north and south hemispheres. The disadvantage is that the galaxies are more distant than those in the Local Group, thus one does not expect to detect much detail or individual stars. We concentrated in learning about the SF through integrated stellar populations from broad-band and Hα CCD imaging.

Our sample was selected from the Virgo Cluster Catalog (Binggeli *et al.* 1985, VCC) with the further proviso that the galaxies would have integrated HI non-zero measurements from Hoffman *et al.* (1987, 1989) and their heliocentric velocity would be less than 3,000 km s^{-1}. The galaxies form two sub-samples, selected according to their surface brightness as reflected by the morphological classification in the VCC. The high surface brightness (HSB) sub-sample is comprised of objects with the BCD classifier (mixed classifications, such as Scd/BCD, are accepted) and is described in Almoznino & Brosch (1998). The low surface brightness (LSB) sub-sample is comprised of ImIV and ImV objects (mixed classifications, such as dE/ImIV, are accepted) and is described in Heller, Almoznino & Brosch (1998). With an apparent magnitude threshold of 17.5 the LSB sub-sample is complete, while the BCD sub-sample is representative and contains ~40% of the candidates in the VCC. Our original sample is, therefore, representative of the dwarf irregular galaxies (DIGs) in the VC.

2. Observational data and their interpretation

The HSB galaxies were observed at the Wise Observatory (WO) in Mizpe-Ramon from 1990 to 1997, with CCD imaging through the B, V, R, and I broad bands, and narrow Hα bandpasses in the rest frame of each galaxy. The LSB galaxies were observed mostly at the WO, with a few images obtained at the 6.0-m BTA telescope in Russia. The data set used in the analysis described here is derived exclusively from Hα line and off-line continuum images flux-calibrated against spectrophotometric standards. The data processing is described in detail by Heller *et al.* (1998 and these proceedings).

We estimate the SFR from the Hα flux using the formalism of Kennicutt *et al.* (1994) for an 18 Mpc distance adopted to the VC: SFR=2.93 10^{11} F(Hα), where F(Hα) is the total line flux in erg s^{-1} cm^{-2} and the SFR is in $M_\odot$ yr^{-1}. Our main finding, explained in more detail by Heller *et al.* (this volume), is that SF takes place both in the HSB and LSB samples. The main difference between the two types of galaxies is the intensity of the phenomenon; HSB objects have SFRs higher by one order of magnitude than LSBs.

We searched for correlations between the SFR and other observable parameters, in order to understand what determines the SFR in DIGs. The search is described in detail in Brosch *et al.* (1998a). The relevant result is that the most significant correlation of the SFR, expressed as the SFR per unit solid angle to compensate for a measure of ignorance of the right distance, was not with the surface gas density nor with a surface gas density and dynamical parameter similar to that put forward by Silk (1997), but simply with the blue surface brightness. In other words, what seems to regulate the SFR in DIGs is the local pre-existing stellar population, as found for large spiral galaxies by Phillipps & Disney (1985).

We confirmed this in Heller *et al.* (1998), where we checked specifically for the link between the Hα flux of an individual HII region and the red continuum flux underneath this HII region; this showed a very strong correlation, supporting our previous result derived with the integrated properties of single galaxies. We conclude that in dwarf irregular galaxies the SFR is regulated by the underlying stellar distribution.

3. Morphology of star formation

A cursory perusal of the net Hα images collected for our entire DIG sample in the VC showed that the HII regions are mostly not centrally located on the galaxy image as shown by the red continuum image. In many cases the HII regions appear right at the edge of a galaxy, mostly to one side. In order to quantify this impression and to eliminate possible biases, due to specific details of our sample galaxies or of our observational procedures, we collected comparison samples of DIGs with Hα and red continuum intensity distribution information from the literature and analyzed them in exactly the same manner as used for the VC DIGs. The comparison samples and their analysis are described in Brosch *et al.* (1998b).

The quantitative analysis required the definition of two morphological indices. The first describes the degree of concentration in the distribution of HII regions and the second represents their measure of asymmetry. In both cases the reference is the red continuum intensity distribution in the galaxy image and the indices are derived using number counts of HII regions. We first determined the center and approximate extent of the red continuum image of each galaxy. This was done by eye-fitting an ellipse to the outermost visible contour of the galaxy's red continuum image and transposing this to the net-Hα image. We then counted the number of HII regions in the inner part of a galaxy, which we defined as the ellipse with the same center and axial ratio as the outer contour ellipse but with axes half the size of those of the outer contour ellipse. The number of HII regions in the inner part of the galaxy was divided by one-third (to compensate for the larger area) of the number of HII regions in the outer annulus, the space between the inner ellipse and the outer one. This ratio we call CI=concentration index and it can range between 0 and ∞. A value of CI=0 indicates a galaxy with HII regions exclusively in the outer part while CI=∞ indicates an object with exclusively central Hα emission.

A second morphological index, representing the asymmetry in the distribution of HII regions, was constructed by counting the number of HII regions on two sides of a bisecting line traced through the center of the ellipse representing the distribution of the red continuum light, which was transposed to the net-Hα image. The position angle of this bisecting line was set so as to maximize the "contrast" in the number of HII regions between the two halves of the image. The asymmetry index AI was then obtained as the ratio between the smaller number and the larger. AI can range between 0 and 1, with a zero value indicating an extremely asymmetric distribution having all HII regions to one side of the bisector line and a value of 1 representing a fully symmetric number distribution.

The distribution of galaxies in the AI-CI plane is shown in Figure 1. It is clear that most objects concentrate at low-AI and low-CI values, indicating that the HII regions are arranged near the edge of a DIG and mostly to one side of it. The points at very low CI are those with CI=0, i.e., galaxies with HII regions only in their outer parts. The concentration at (CI=100, AI=0) represents points with exclusively nuclear Hα emission; these are essentially BCDs and have CI=∞.

The tendency of DIGs to have asymmetric distributions of HII regions is emphasized by Figure 2, which is a histogram of the distribution of the AI index. Far from being a symmetric Gaussian around AI=0.5, as one could expect for a random distribution of spotty HII regions over the galaxies, the figure shows most objects with AI$\leq$0.5. If we eliminate the bin with AI$\approx$0, which represents those objects with $\sim$one HII region, we have slightly more galaxies in the AI$\geq$0.5 part of the distribution but the difference is not significant; the strong indication of asymmetry is thus driven by objects with few or single HII regions where the SF is generally not centered on the red light distribution. Objects which are not "extreme", i.e., AI$\neq$0 and CI$\neq$ ∞, seem to define a tendency of a more symmetric SF pattern the more centrally concentrated the SF is.

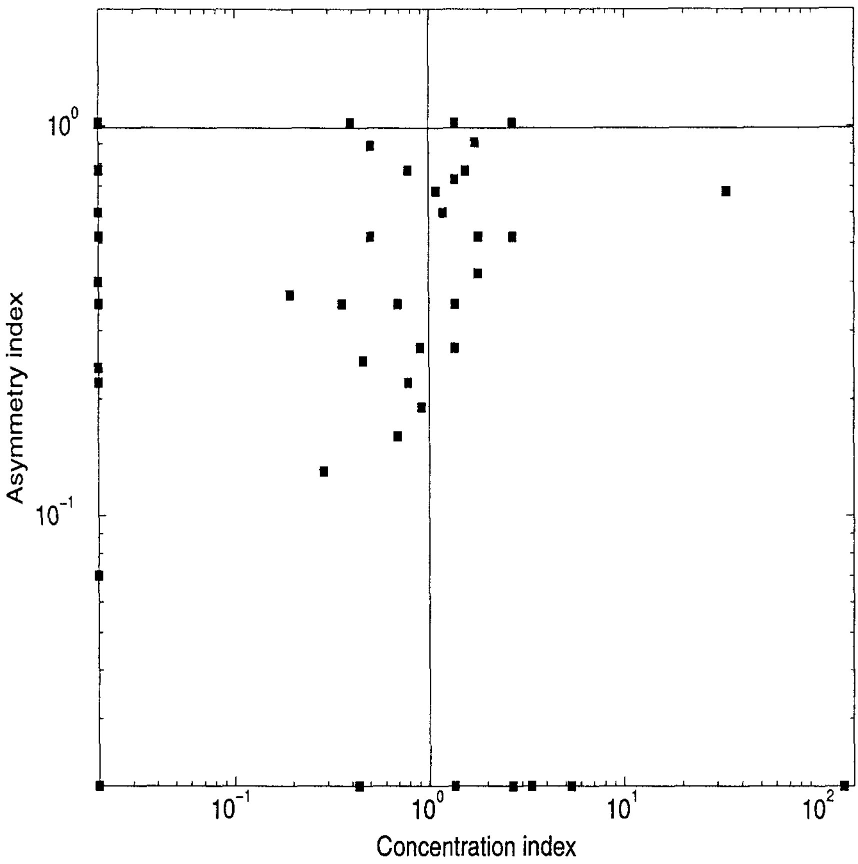

Figure 1. Distribution of the asymmetry and concentration indices. We indicate AI=1 (i.e., a fully symmetric distribution of HII regions) by a horizontal line. The vertical line indicates CI=1 (i.e., an equal number density of HII regions between the inner and outer parts of a galaxy). Most of the objects concentrate in the low AI bins, indicating a preference for asymmetric distribution of HII regions.

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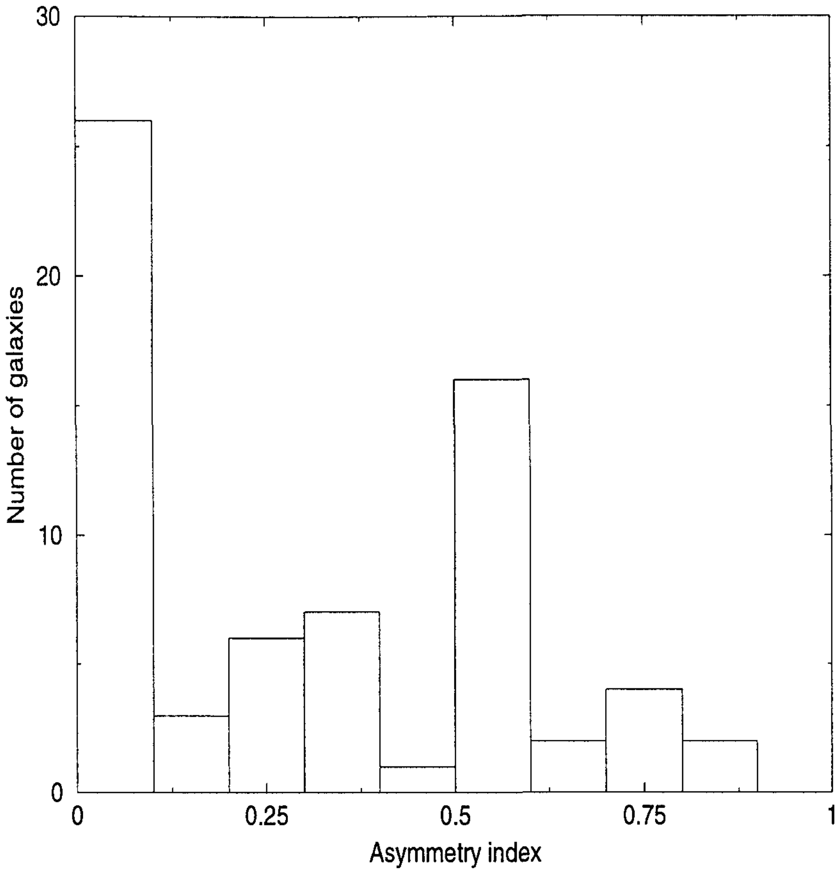

Figure 2. Histogram of the asymmetry index for all the sample galaxies, indicating that the majority have AI$\leq$0.5. This behavior is driven by the large number of objects with a few, or just one, HII region. In such cases, the HII regions have a higher probability of not being located exactly in a symmetric location with respect to the red light distribution.

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4. Discussion

We have demonstrated that there is inherent asymmetry in the distribution of star-forming regions in DIGs, and that these regions tend to reside in the outer parts of these galaxies. This is **not** a new discovery, as Hodge (1969) already remarked on the asymmetrical distribution of HII in a small number of DIGs. His seven objects were selected to be very near and could be analyzed on well-resolved photographic images. He checked the asymmetry by counting HII regions on different sides of a galaxy, where the reference mid-galaxy bisector was that of the HII region distribution itself. However, Hodge did not discuss the possible origin of this asymmetry.

The asymmetry and degree of concentration of light in galaxies have been used as morphological indicators for the barely resolved galaxies of the HST Medium Deep Survey (MDS: Abraham *et al.* 1996). There are differences between these indices and those used by us: firstly, the analyzed MDS images are broad-band I (representing the distribution of evolved stars), while we use net-Hα images (i.e., the pattern of newly formed stars). Secondly, our indices are based on eyeball number counts of HII regions, while those of Abraham *et al.* are calculated by "impartial" algorithms from fluxed images. The comparison sample at low redshift, from which Abraham *et al.* derived their calibration of the A & C indices against morphological types, lacks a good representation of irregular galaxies. Nevertheles, they concluded that the late-type galaxies (Sdm and Irr) in the MDS are concentrated at low A & C values, just as we find for our star-forming DIGs. This, they proposed, is evidence for the evolution of irregular galaxies.

Gerola & Seiden (1978) proposed the stochastic self-propagating SF (SSPSF) as a possible regulatory mechanism. Their simulations, as well as those by Jungwiert & Palous (1994), produce preferentially flocculent or grand-design spirals. There are no specific calculations for DIGs which show "snapshots" of the SF proceeding with time through the galaxy. If the galaxy is small, and a number of SNs explode off its center, it may be possible for a compression wave to form stars in suitable location while escaping from the galaxy in places where the ISM is thin or altogether absent. This could, in principle, give rise to an asymmetric pattern of SF and can be examined in a nearby DIG (Ho II: Puche *et al.* 1992). The Hα and off-line images show that Ho II forms stars near its center. The Hα emission originates either at the interfaces between large holes in the HI distribution or in small HI holes. Thus this case does not support the SSPSF forming stars asymmetrically or at the edges of a galaxy.

O'Neil, Bothun & Schombert (1998) argued that the SF trigger in LSB disks is distant tidal interactions. Specifically, they combined arguments from Vázquez & Scalo (1989), that tidally-induced starbursts may be considerably delayed after a gas density enhancement, with simulations from Mihos, de Block & McGaugh (1997) who showed that collisions of LSBs with compact galaxies produce long-lived disturbances in the LSB disks. Although this may operate in large LSB galaxies, serving there as SF triggers, the mechanism is probably not relevant for SF in DIGs. This is because disky DIGs tend to be more stable than large galaxies. Also, the simulations of Mihos *et al.* (1997) showed that the tidally-induced distortions in LSBs form mostly spiral arms and inner rings;

it is probable that any subsequent SF event will retain the same geometry which is a form of density wave and is not the asymmetry which we observe in DIGs.

Icke (1985) proposed a mechanism by which distant tidal interactions may trigger SF through shocks in the ISM of gas-rich disks. His mechanism is probably not relevant for the case of DIGs, because the real strength of the interaction is likely to be much weaker than he estimated. The reason is that the geometrical factor **g** which Icke uses to account for the configuration of the interaction is most likely <0.05, and not 0.39 as fitted by Icke. The factor **g** drives the strength of the tidal interaction and to keep this at the required level one needs to correct upward another parameter in the relation. This is probably very unlikely, making Icke's work not relevant to SF triggers in DIGs. These all argue against tidal interactions as being SF triggers in DIGs, as Heller et al mention here.

Rudnick & Rix (1998) discussed the asymmetry of early-type disk galaxies. They used a different algorithm than ours or that of Abraham *et al.* (1996) to detect asymmetry; the amplitude of the m=1 azimuthal Fourier coefficient of the surface brightness in the R-band. Their claim is that the R-band samples stellar populations older than 1 Gyr, thus the asymmetry found in these disks must be an inherent property of the stellar mass distribution. However, this asymmetry in the mass is not followed by them in the SF properties.

A similar form of asymmetry, lopsidednes of a galactic disk, has also been studied by Jog (1997). Its cause is the asymmetric motion of particles in a lopsided halo. Jog also showed that the gravitational coupling of stars and gas would tend to make the gas more unstable in such a situation than if the gas should be self-gravitating (Jog 1996, 1998). This effect would enhance the asymmetry observed in the young stars in comparison with any asymmetry shown by the old star component. Another explanation for the asymmetry of disks has been proposed by Levine & Sparke (1998). Their scenario has the disk orbiting in an off-center location in the galaxy's DM halo and spinnig in a retrograde sense to its orbital motion. It is not clear what implication do these models have on the asymmetry of SF in DIGs; they refer mostly to collisionless particle simulations of disks while the behavior we witness in DIGs is manifested by the dissipative component of a galaxy, its ISM. However, if the asymmetry of disks or halos implies a similar asymmetry of the gravitational potential, this could serve as a trigger for the asymmetric SF we observe in DIGs.

5. Conclusions

We have shown that star formation takes place in both HSB and LSB DIGs, and that the difference between the two flavors of DIGs is the intensity of the phenomenon. A consideration of a large sample of DIGs has demonstrated that these galaxies tend to form stars in an asymmetric pattern at their outer edge. We could not identify the mechanism responsible for this behavior, but suggest that some asymmetry in the gravitational potential of the galaxies may be the cause.

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