STAR FORMATION IN DWARF GALAXIES

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ABSTRACT

We explore mechanisms for the regulation of star formation in dwarf galaxies. We concentrate primarily on a sample in the Virgo Cluster, which has H I and blue total photometry, for which we collected Hα data at the Wise Observatory. We find that dwarf galaxies do not show the tight correlation of the surface brightness of Hα (a star formation indicator) with the H I surface density, or with the ratio of this density to a dynamical timescale, as found for large disk or starburst galaxies. On the other hand, we find the strongest correlation to be with the average blue surface brightness, indicating the presence of a mechanism regulating the star formation by the older (up to 1 Gyr) stellar population if present, or by the stellar population already formed in the present burst.

Subject headings: galaxies: irregular — galaxies: stellar content — H II regions — stars: formation

1. INTRODUCTION

Star formation (SF) is a fundamental process in the evolution of galaxies and is far from being well understood. The SF is usually characterized by the initial mass function (IMF) and the total SF rate (SFR), which depends on many factors, such as the density of the interstellar gas, its morphology, its metallicity, etc. According to Larson (1986), four major factors drive star formation in galaxies: large-scale gravitational instabilities, cloud compression by density waves, compression in a rotating galactic disk due to shear forces, and random cloud collisions. In galaxies with previous stellar generations additional SF triggers exist, such as shock waves from stellar winds and supernova explosions. In dense environments, such as clusters of galaxies and compact groups, tidal interactions, collisions with other galaxies, interstellar matter (ISM) stripping, and cooling flow accretion probably play some role in triggering the SF process. The triggering mechanisms were reviewed recently by Elmegreen (1998).

While “global” phenomena, such as the first two SF triggers of Larson (1987), play a large part in grand design spirals, random collisions of interstellar clouds may provide the best explanation for dwarf galaxies with bursts of SF. Because of their small size, lack of strong spiral pattern, and sometimes solid-body rotation (e.g., Martin, Carignan, & Roy 1994; de Blok & McGaugh 1997), the star formation in dwarf galaxies is not triggered by compression due to gravitational density waves or by disk shear. Therefore, understanding SF in dwarf galaxies should be simpler than in other types of galaxies.

The characterization of the SF processes by a star formation rate (SFR) controlled by the interstellar gas density as a power law was first introduced by Schmidt (1959). The volume density of young stars, \( \rho_\ast \), is related to the volume density of H I gas in the Galactic disk as \( \rho_\ast = a \rho_{\text{gas}}^n \), where \( a \) is a constant, probably \( \approx 2 \) for spiral galaxies. In other galaxies the convention is to express the quantities as projected densities of stars (\( \Sigma_\ast \)) and of gas as actually observed: \( \Sigma_\ast = A \Sigma_{\text{gas}}^a \). This is usually studied by correlating the surface density of a young star tracer, such as the Hα surface brightness, with the gas column density.

The Hα emission from a galaxy measures its ongoing SFR (Kennicutt 1983). Gallagher, Hunter, & Tutukov (1984) derived an analytic relation between the detected Hα flux and the present SFR of a galaxy; similar relations were derived by Kennicutt, Tamblyn, & Congdon (1994). The blue luminosity of a galaxy, on the other hand, measures its past star formation integrated over the last \( \sim 10^9 \) yr (Gallagher et al. 1984). The newly formed stars, of which the more massive produce the Lyman continuum photons that ionize hydrogen and produce the Hα emission, also contribute to the blue-light output of a galaxy. This contribution is minor in comparison to that from the stars already existing in a galaxy unless the SF event is the first in the history of the galaxy or the starburst is unusually strong. Interestingly, Tresse & Maddox (1998) found recently that the Hα luminosity of a galaxy correlates with its blue absolute magnitude.

Kennicutt (1998) found that his parameterization of the Schmidt law fitted well the SF pattern of spiral and IR-selected starburst galaxies. An alternative to the Schmidt law, proposed by Silk (1997), fitted equally well. In this variant, the SFR per unit area scales with the ratio of the gas surface density to the local dynamical timescale: \( \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}/\tau_{\text{dyn}} \propto \Sigma_{\text{gas}} \Omega_{\text{gas}} \), where \( \Omega_{\text{gas}} \) is the angular rotation speed and the scenario fits disk configurations. Kennicutt (1998) adopted \( \Omega_{\text{gas}} = V(R)/R \), where \( V(R) \) is the rotation velocity of the gas at a distance \( R \).

Hunter, Elmegreen, & Baker (1998) tested a set of SF predictors on two small samples of dwarf galaxies, one measured by them and another derived from de Blok (1997). They found that the ratio of \( \Sigma_{\text{gas}} \) to the critical density for the appearance of ring instabilities did not correlate with the star formation, but that the stellar surface brightness did. From this, they concluded that possibly the stellar energy input provides the feedback mechanism for star formation.
We concentrate on a sample of late-type dwarf galaxies in the Virgo Cluster (VC). The reason for selecting dwarfs was to limit the number of possible trigger mechanisms of SF; these objects are devoid of large-scale SF triggers, as explained above. Having only VC members limits the sample to a well-defined galaxy background; in addition, all objects are at approximately the same distance and have HI information from the same source. We tested for correlations between the Hα emission and other observed quantities, in order to investigate mechanisms which regulate SF in dwarf galaxies. The justification to correlate the Hα SFR index against \( \Sigma_{\text{gas}} \) is the finding of Kennicutt (1998) that a Schmidt-type law seems to fit large galaxies. If the SFR depends on the ratio of the gas density to the dynamical timescale (Silk 1997; Kennicutt 1998), a correlation with \( \Sigma_{\text{gas}} \) is expected. Finally, if the SFR depends on the local population of blue stars, as found by Hunter et al. (1998), then a dependence on the average blue surface brightness is expected. We also tested the SFR against the ISM gas density, in a manner similar to that suggested by Silk (1997).

2. THE SAMPLE

Our sample consists of 52 late-type dwarf galaxies in the VC selected from Binggeli, Sandage, & Tamman (1985, hereafter VCC) with HI measurements from Hoffman et al. (1987, 1989). The sample was constructed in order to enable the detection of weak dependencies of the star formation properties on hydrogen content and surface brightness. We selected two subsamples by surface brightness: one represents a high surface brightness (HSB) group and is either Blue Compact Dwarf (BCD) or anything + BCD, and another represents a low surface brightness (LSB) sample and includes only Im IV or Im V galaxies. The morphological classification, which bins the dwarf galaxies in the HSB or LSB groups, is exclusively from the VCC. In addition, the galaxies are binned by their HI flux integral (FI) from Hoffman et al. (1987, 1989). The HSB subsample was selected with galaxies of high HI content (FI > 1500 mJy km s\(^{-1}\)) or with low HI content (0 < FI < 600 mJy km s\(^{-1}\)) and is described in Almoznino & Brosch (1998, hereafter AB98). The LSB subsample has FI > 1000 for the high-HI sample or 0 < FI < 700 mJy km s\(^{-1}\) for the low-HI sample (described in Heller et al. 1998, hereafter HAB98). The LSB subsample is complete, in the sense that it contains all objects classified Im IV or Im V in the VCC with \( m_B > 17.2 \) mag. The HSB subsample contains 45% of the VCC galaxies of this type with \( m_B < 17.2 \). Although not complete, it is representative of this type of object in the VC.

The galaxies were observed at the Wise Observatory (WO) in Mizepe-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 discussion of all observations and their interpretation is the subject of other papers (AB98; HAB98). We restrict the discussion here to the analysis of the integrated Hα flux \( F(\text{H}\alpha) \) as it reflects on the global process of SF. In particular, we concentrate on correlations of this SFR index with other parameters collected from the literature.

We compare our results with other dwarf galaxies for which we collected published data. We selected Case galaxies from Salzer et al. (1995) of types HIIH, DHIH, BCD, MagIr, and GIIr, as most similar to our VC sample. We further required that HI observations would exist for the Case galaxies and collected seven such objects. As these galaxies do not have total Hα fluxes listed, we estimated those (1) from the total blue magnitude \( m_B \), (2) from the listed equivalent width of the H\( \beta \) line, and (3) by assuming H\( \alpha \)/H\( \beta \) = 2.9 (case B, with no extinction). A second comparison sample of eight galaxies originates from Martin (1997), where each object has an average Hα surface brightness measured in the 1" wide slit. FI and \( \sigma(\text{HI}) \) values were collected from Huchmeier & Richter (1989), while total blue magnitudes and sizes originate from the NASA Extragalactic Database. No corrections for Galactic or internal extinction were applied to the data. We also assumed that the Balmer emission observed spectroscopically is representative of the entire galaxy.

Here we prefer to use distance-independent measures, which are not sensitive to the exact location of a galaxy in the VC, to the value of \( H_0 \) or to deviations from a smooth Hubble flow, and to stick, as much as possible, to directly observable quantities. The observables \( F(\text{H}\alpha) \), FI, and \( m_B \) have, therefore, been normalized to the optical area of each galaxy, yielding “surface brightness” measures per square arcminute. We calculated average blue surface magnitudes \( \Sigma(B) \), average H\( \alpha \) flux integrals per unit surface \( \Sigma(\text{HI}) \), and average H\( \alpha \) surface brightnesses \( \Sigma(\text{H} \alpha) \) for all objects. The optical area of a galaxy is defined here as \( A = \pi D^2/4R \), with \( D \) the major axis in arcminutes and \( R \) the axial ratio listed in VCC or estimated from the image of the object on the Digitized Sky Survey, to yield \( \Sigma(\text{HI}) \).

We used in some correlations \( \sigma(\text{HI}) \) and derived \( \Omega = \sigma(\text{HI})/D \) as a representative gasdynamical property at the outermost optical radius. This definition of \( \Omega \) is not purely equivalent to that used by Kennicutt (1998), but it does not require cosmological assumptions in its derivation. We caution at this point that \( \Sigma(\text{HI}) \) may overestimate the surface density of HI in cases where the hydrogen distribution extends beyond the optical area of an object. Cases where the HI distribution was 3 times and more larger than the optical size of a galaxy were reported by Taylor et al. (1995). However, while very extended HI distributions do exist, they are not a general characteristic of dwarf galaxies. G. L. Hoffman (1997, private communication) found that only two of the five Virgo Cluster BCDs mapped at Arecibo showed evidence for being extended. In most cases, the Arecibo beam will cover more than 3 times the optical size of one of our objects, implying that not much HI could have been missed in the measurements we use here. In the absence of synthesis or multibeam mapping of the HI distributions, we elected to use the coarse measure of \( \Sigma(\text{HI}) \) as defined here, with all caveats mentioned.

The WO sample ranges over more than 2 orders of magnitude in \( \Sigma(\text{HI}) \), over more than 3 orders of magnitude in \( \Sigma(\text{H} \alpha) \), and over slightly less than 2 orders of magnitude in \( \Sigma(B) \). The comparison sample from Salzer et al. (1995) is more restricted in the range of H\( \alpha \), while the galaxies from Martin (1997) have more intense H\( \alpha \) than the WO objects. In general, galaxies from Salzer et al. are about twice as distant as the VC sample, while objects from Martin are \(~3\) times closer than the VC.

3. STAR FORMATION CORRELATIONS

We first checked correlations between global parameters of our dwarf galaxy sample, such as total blue brightness,
total HI content, etc. In all correlations we considered only detected quantities (no upper limits were included). We did not find that $m_B$ and the HI FIs were correlated in any of the subsamples (for the entire WO sample the correlation coefficient was 0.57, $F = 17.4$). This scatter plot is shown in the top left panel of Figure 1. Note that some degree of correlation would be expected only from the distance effect, with both $m_B$ and FI being lower for more distant objects.
The plot of $\Sigma(B)$ versus $\Sigma(H\text{ I})$, shown in the top right panel of Figure 1, indicates that galaxies with more $H\text{ I}$ per unit area tend also to have higher blue surface brightness, i.e., a higher past-averaged SFR, but this correlation was not very significant. We found that $\log \Sigma(Hz)$ correlates with the $H\text{ I}$ line width (correlation coefficient $0.61$, $F = 21.3$) and show this in the left middle panel of Figure 1. Dwarf galaxies with brighter blue surface brightness tend also to have wider $H\text{ I}$ profiles (correlation coefficient $0.51$, $F = 13.6$), as the right middle panel of Figure 1 shows. That $\Sigma(H\alpha)$ correlates weakly with $\sigma(H\text{ I})$ is illustrated in the lower left panel of Figure 1.

Kennicutt (1998) showed that in a sample of large spirals and starburst galaxies the average $Hz$ disk surface brightness correlates well with the average molecular and atomic gas surface density. Dwarf galaxies have very small quantities of molecular gas (e.g., Gondhalekar et al. 1998); therefore, using $\Sigma(H\text{ I})$ here should well represent the total ISM.

This correlation, shown in the lower right panel of Figure 1, was also weak, and the combined WO sample had a correlation coefficient of only $0.52$ ($F = 13.1$).

A better correlation was found for $\Sigma(Hz)$ versus the "Silk"-type parameter $\Sigma(H\alpha)$. Figure 2 shows this for the two VC samples (HSB = filled diamonds, LSB = squares), as well as for the comparison samples from Salzer et al. (1995; triangles) and Martin (1997; filled circles).

Note that the two VC samples join up nicely, with the HSB galaxies being brighter and more Hz-intense than the LSB objects. The correlation coefficient for the combined WO sample is $0.70$ ($F = 34.2$) and the slope is $0.93 \pm 0.16$. The log $\Sigma(Hz)$ correlates even better with the blue surface magnitude, as Figure 3 shows. For the combined WO sample the correlation coefficient is $0.77$ and the slope is $-0.63 \pm 0.09$ ($F = 51.2$).

The Salzer et al. (1995) and Martin (1997) galaxies deviate in both plots from the trend set by the VC sample. Some of the discrepancy may be the result of our samples being measured in a uniform and consistent manner, whereas the plotted parameters for the comparison samples were calculated from published data and some assumptions (explained above). The Martin galaxies appear consistently above the location of the WO galaxies; it is probable that their total Hz flux was overestimated by assuming that the slit average is representative of the entire galaxy. This is confirmed for the three objects in common with Marlowe, Meurer, & Heckman (1997), which have consistently lower total Hz fluxes than adopted by us here. The Salzer et al. (1995) objects are generally below the WO objects. They have significant extinction ($<c_z> \approx 0.77$), which translates into an underestimate of the Hz emission when scaling from the $H\beta$ flux. In addition, the $H\beta$ fluxes were not corrected for underlying absorption; this also causes an Hz underestimate. Other reasons for discrepancies may be the different distances to the two comparison samples, which influence $\Omega$ through the angular diameter of a galaxy, used in the present derivation.

4. DISCUSSION

We mentioned above a number of triggers of star formation. Some, such as shear and two-fluid instabilities or spiral density waves, are important mainly in large disk galaxies and thus are not relevant for dwarfs. The sample studied here is composed of fairly isolated galaxies, although this was not a selection criterion. The galaxies are distant enough from other objects to discount recent (a few times $10^7$ yr) interactions as possible SF triggers. In these dwarfs the expectation is that the SF may be regulated only by the gas density, or by the gas density combined with some factor connected with the stellar content of the galaxy. We checked here various correlations of the star formation indicator $\Sigma(Hz)$ with global or specific (per unit area) galaxy parameters. The "expected" correlations, observed by Kennicutt (1998) to fit spiral galaxies, were found to be much weaker in dwarfs. The strongest correlation was with $\Sigma(B)$, while the local ISM dynamic indicator $\Sigma(H\alpha)\Omega$ showed the second-strongest correlation.

The correlation found for the Canada-France Redshift Survey galaxies ($<c_z> \approx 0.2$; Tresse & Maddox 1998), between the global $M_g$ and $\log L(Hz)$, can be understood if that survey preferentially selected galaxies of similar sizes in blue and in hydrogen emission, reducing the problem to a correlation between area-normalized quantities. These gal-
axies are much brighter ($M_B \geq -21$ mag) than the dwarfs
discussed here and, being selected on the basis of their
$I$-band emission, are probably not representative of the
“star-forming dwarfs” class.

Our findings support a scenario whereby the SF is not
controlled by the gas volume density, by its surface density,
or by the ratio of the gas surface density to a local dynamical
timescale. The strongest correlation, based on the corre-
clation coefficient and the value of the $F$-statistic, was with
the average blue surface magnitude, as also found by
Hunter et al. (1998). There the question was posed whether
this was an effect of the SFR being nearly constant over the
last $\sim 1$ Gyr. We can definitely rule out this possibility, as at
least one of our objects (VCC 144; Brosch, Almoznino, &
Hoffman 1998) seems to exhibit its first SF burst. Many
other galaxies, mainly from the LSB sample, show a number
of small H II regions indicating localized SF at present. The
colors (AB98) are best fitted by (at least) two stellar popu-
lations formed in short bursts, spaced a few 100 Myr to 1
Gyr apart. This indicates that a constant SF is not a serious
possibility for the dwarf galaxies studied here.

5. CONCLUSIONS

We tested correlations among parameters related to SF,
gas and stellar content, and internal dynamics on a sample
of dwarf galaxies in the Virgo Cluster. We found that both
the Schmidt law and the more recent relation derived by
Silk (1997) do not fit these galaxies as well as they do spirals
(Kennicutt 1998). The strongest correlation of the Hz
surface brightness, which measures the present SF strength,
was with the average blue surface brightness, supporting the
proposition of Hunter et al. (1998) that a feedback mecha-
nism must be at work to regulate the present SF by the
older stellar population.

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