Small Bites: star formation recipes in extreme dwarfs

Sambit Roychowdhury,1⋆ Jayaram N. Chengalur,1⋆ Serafim S. Kaisin,2⋆ Ayesha Begum3⋆ and Igor D. Karachentsev2⋆

1NCRA-TIFR, Post Bag 3, Ganeshkhind, Pune 411 007, India
2Special Astrophysical Observatory, Russian Academy of Sciences, N. Arkhyz, KChR 369167, Russia
3Department of Astronomy, University of Wisconsin-Madison, Madison, WI 53706-1582, USA

Accepted 2011 March 29. Received 2011 March 22; in original form 2011 January 11

ABSTRACT

We study the relationship between the gas column density (ΣgH) and the star formation rate surface density (ΣSFR) for a sample of extremely small (MB ∼−13, ΔV50 ∼30 km s−1) dwarf irregular galaxies. We find a clear stochasticity in the relation between the gas column density and star formation. All gas with ΣgH > 10 M⊙ pc−2 has some ongoing star formation, but the fraction of the gas with ongoing star formation decreases as the gas column density decreases and falls to about 50 per cent at ΣgH ∼ 3 M⊙ pc−2. Further, even for the most dense gas, the star formation efficiency is at least a factor of ∼2 smaller than typical of star-forming regions in spirals. We also find that the ratio of Hα emission to far-ultraviolet emission increases with the increasing gas column density. This is unlikely to be due to increasing dust extinction because the required dust-to-gas ratios are too high. We suggest instead that this correlation arises because massive (i.e. Hα-producing) stars are formed preferentially in regions with high gas density.

Key words: galaxies: dwarf – galaxies: irregular – galaxies: star formation – radio lines: galaxies.

1 INTRODUCTION

Models of galaxy formation and evolution generally use semiempirical ‘recipes’ to follow the process of star formation (e.g. Springel et al. 2005; Governato et al. 2010). Typically, star formation is assumed to set in only above a ‘threshold’ gas (column) density Σgas and beyond that to be proportional to a power of Σgas. This is supported by observations of nearby star-forming galaxies (e.g. Schmidt 1959; Kennicutt 1998b). However, most of these observations are of large spiral galaxies, whereas from the hierarchical galaxy formation model, one would expect that the first formed systems were much smaller than the typical z ∼ 0 spiral. Here we study the relation between gas and star formation in nearby, extremely faint (MB ∼−13, ΔV50 ∼30 km s−1) gas rich dwarfs.

The dwarf galaxies in our sample are dynamically and structurally very different from the large spiral galaxies for which the widely used star formation recipes have been derived. First, in our sample galaxies, the rotation velocity is not much larger than the velocity dispersion (e.g. Begum, Chengalur & Hopp 2003; Begum et al. 2008a). Further, the gas does not settle into a thin disc; the mean dispersion (e.g. Begum, Chengalur & Hopp 2003; Begum et al. 2010) find that in the HI-dominated outskirts of spiral galaxies, the SFR and HI column density are correlated, albeit with a scatter.

In this Letter, we extend our previous work in two important directions. First, we try to quantify the stochastic nature of the relationship between ΣSFR and ΣHI. Secondly, we also study the relationship between the gas column density and the formation of stars of different masses.
and that the galaxy has had continuous star formation over time-scales of $10^7$ yr or longer. The implications of these assumptions are discussed in Section 3.

Details of the Hα data reduction can be obtained from Karachentsev & Kaisin (2007) and Kaisin & Karachentsev (2008). The images were corrected for dust extinction due to our own Galaxy in a similar way to that followed for the FUV maps. The Hα luminosity was converted to SFRs using the calibration given in Gallagher, Hunter & Tutukov (1984):

$$\text{SFR} \left( M_\odot \text{yr}^{-1} \right) = 1.06 \times 10^{-28} L_\alpha \left( \text{erg s}^{-1} \right).$$  \hfill (2)

The assumptions used to derive this calibration are the same as that used in deriving the FUV flux–SFR calibration.

For data from all three wavelengths, relevant parameters ($\Sigma_{\text{HI}}$ and $\Sigma_{\text{SFR}}$) were calculated over several scales. (a) An average over the entire star-forming disc of the respective galaxy (i.e. ‘global’ values). The ‘star-forming disc’ is defined as that within the radius at which the SFR is $1.85 \times 10^{-4} M_\odot$ yr$^{-1}$ kpc$^{-2}$ (as measured from the FUV flux, with the GALEX images smoothed to 400-pc linear resolutions). This approximately corresponds to the $B$-band Holmberg diameter for those sample galaxies for which the Holmberg diameter has been measured. (b) ‘Pixel’ values. We define ‘pixels’ as squares which in turn Nyquist sample squares 400 pc or 150 pc in size. For the H1 images, 400-pc-resolution images are available for all the galaxies in our sample. Similarly, for the FUV data, 150-pc-resolution images are available for all galaxies.

Fig. 1 shows Hα grey-scale images overlaid with FUV and H1 contours, for a representative galaxy in our sample.

### 3 RESULTS AND DISCUSSION

Fig. 2(a) shows the relationship between the disc-averaged $\Sigma_{\text{SFR}}^\text{Hα}$ (and corresponding $\Sigma_{\text{SFR}}^\text{FUV}$) and $\Sigma_{\text{HI}}$, for the galaxies in our sample with Hα data. Note that the galaxies are forming stars even though their typical gas density is at or below the ‘threshold density’. Panel (b) shows how the global $\Sigma_{\text{SFR}}$ estimates obtained using the two different tracers relate. Although the SFR tracers do correlate, there is a considerable scatter about the 1:1 line. Note that the data agree better with the original calibration suggested by Kennicutt (1998a) than with the recalibration suggested by Lee et al. (2009a), though it should be noted that the latter sample is much larger than ours. In terms of the total SFR, the values range from $2.79 \times 10^{-4}$ to $1.05 \times 10^{-2} M_\odot$ yr$^{-1}$ with FUV as a tracer and from $2.33 \times 10^{-4}$ to $1.21 \times 10^{-2} M_\odot$ yr$^{-1}$ with Hα as a tracer. Finally, following Hunter, Elmegreen & Ludka (2010) we show in panel (c) the ratio $\Sigma_{\text{SFR}}^\text{FUV}/\Sigma_{\text{SFR}}^\text{Hα}$ as a function of $\Sigma_{\text{HI}}$. There is a clear correlation and the best-fitting line has a slope of $-0.63 \pm 0.09$ (compared to $-0.59$ obtained by Hunter et al. 2010). The SFR calibration we used assumes solar metallicity, however, as discussed in detail by Hunter et al. (2010), the fact that the dwarf galaxies have lower than solar metallicity has only a marginal effect on the $\Sigma_{\text{SFR}}^\text{FUV}/\Sigma_{\text{SFR}}^\text{Hα}$ ratio, since both calibrations are similarly affected.

In what follows, we take a look at the relationship between gas and star formation on small scales, by making ‘pixel-by-pixel’ comparisons of $\Sigma_{\text{HI}}$ and $\Sigma_{\text{SFR}}$. We first focus on the stochasticity in the star formation and return to the comparison between $\Sigma_{\text{SFR}}^\text{Hα}$ and $\Sigma_{\text{SFR}}^\text{FUV}$ in Section 3.2.

#### 3.1 Stochasticity in star formation

R09 showed that, from a comparison of the FUV and H I images, in star-forming regions $\Sigma_{\text{SFR}}^\text{FUV}$ and $\Sigma_{\text{HI}}$ are related as

$$\log \Sigma_{\text{SFR}}^\text{FUV} = (1.81 \pm 0.05) \log \Sigma_{\text{HI}} - 4.70 \pm 0.05.$$  \hfill (3)

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By comparison with the canonical KS law,
\[
\log \Sigma_{\text{SFR}} = (1.4 \pm 0.15) \log \Sigma_{\text{gas}} - 3.60 \pm 0.14,
\]
and noting that (i) \( \Sigma_{\text{HI}} \) is a strict lower limit to the total \( \Sigma_{\text{gas}} \) and (ii) for a given FUV flux, the inferred SFR decreases with decreasing metallicity, the robust conclusion that one can draw is that the star formation process in dwarf galaxies is significantly less efficient than that in big galaxies. R09 also showed (see their fig. 6) that the data implied stochasticity and were best modelled as a stochastic power law with a variation of 50 per cent in the coefficient (as opposed to the slope) of the power law. Begum et al. (2006) had also highlighted the stochasticity in the relation between \( \Sigma_{\text{SFR}} \) and \( \Sigma_{\text{HI}} \) in dwarf galaxies. To properly characterize the star formation process, one would hence also need to know the average fraction of the gas that is participating in star formation.

Fig. 3 shows the fraction of pixels which are observed to be star forming (i.e. have a SFR of at least 3\( \sigma \), where \( \sigma \) is the rms in the UV image, in units of the SFR). The plot averages over 16 of the original sample of 23 galaxies; seven galaxies with relatively low GALEX exposure times have been excluded. The dashed vertical lines indicate the rms level (after being translated from \( \Sigma_{\text{SFR}} \) to \( \Sigma_{\text{HI}} \) using equation 3). For a given galaxy, if there was no stochasticity in the star formation, then all points above the rms level (right-hand side of the corresponding dashed line) should have had observable star formation. As such, all points to the right-hand side of the rightmost dashed line can hence be regarded as giving a reliable fraction of the gas that is participating in star formation. There are several points worth noting. (1) All pixels with gas density greater than \( \sim 10 M_\odot \text{pc}^{-2} \) participate in star formation. Interestingly, this number is identical to the threshold density for star formation of \( \sim 10^3 \text{atoms cm}^{-2} \) proposed by Skillman (1987).

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Figure 1. Overlays of the H\( \alpha \), UV and H I images for UGC 685. Panel (a): grey-scales – H\( \alpha \) (in \( 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \) per pixel of area 0.1225 arcsec\(^2\)); contours – GALEX FUV image (from 0.0014 to 0.032 counts s\(^{-1}\) per pixel of area 2.25 arcsec\(^2\), in steps of 2). Panel (b): grey-scales – H\( \alpha \); contours – GMRT H I image (from 17.5 to 1120 Jy beam\(^{-1}\) in s\(^{-1}\) in steps of \( \sqrt{2} \)). Panel (c): grey-scales – GALEX FUV (in \( 10^{-3} \) counts s\(^{-1}\) per pixel of area 2.25 arcsec\(^2\)); contours – GMRT H I image. Respective resolutions are: H\( \alpha \) – 1.9 arcsec; FUV – 4 arcsec; H I – 17 \( \times \) 16 arcsec\(^2\). The length of the bold line in panel (a) is approximately 1 kpc.

Figure 2. Panel (a): \( \Sigma_{\text{SFR}} \) derived from H\( \alpha \) (\( \Sigma_{\text{SFR}}^{\text{H}\alpha} \), empty squares) and FUV (\( \Sigma_{\text{SFR}}^{\text{FUV}} \), filled circles) plotted against \( \Sigma_{\text{HI}} \), assumed to represent \( \Sigma_{\text{gas}} \), both axes being in log scale. The solid line represents the Kennicutt–Schmidt (KS) law with a slope of 1.4 and the dashed line represents the best-fitting Schmidt law for spiral galaxies only, both taken from Kennicutt (1998b). The shaded region covers various estimates of the ‘threshold density’ tabulated in Kennicutt (1989). Panel (b): disc-averaged values of \( \Sigma_{\text{SFR}}^{\text{H}\alpha} \) and \( \Sigma_{\text{SFR}}^{\text{FUV}} \). The solid line is the 1:1 line and the dashed line represents the relationship found by Lee et al. (2009a). Panel (c): ratio of global \( \Sigma_{\text{SFR}}^{\text{H}\alpha} \) to \( \Sigma_{\text{SFR}}^{\text{FUV}} \). The dashed line is the best-fitting straight line and has a slope of \( -0.63 \). The vertical dot–dashed line shows the approximate \( \Sigma_{\text{SFR}} \) value for our sample galaxies below which the SFR estimated assuming a Salpeter IMF will start deviating from the true SFR according to Pflamm-Altenburg, Weidner & Kroupa (2007). See the text for more details.

Figure 3. Plot of the fraction of gas that is ‘participating in star formation’ as a function of \( \Sigma_{\text{HI}} \). The plot averages over 16 galaxies; the dashed horizontal lines indicate the rms level of the UV images of the individual galaxies (after being translated from \( \Sigma_{\text{SFR}} \) to \( \Sigma_{\text{HI}} \) using equation 3). All points to the right-hand side of the rightmost dashed line can be regarded as giving a reliable fraction of the gas that is participating in star formation. The solid line is a fit to the ‘reliable’ points. See text for more details.

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efficiency (i.e.\(\eta\)). Thus, even for the densest gas in dwarf galaxies, the star formation (2) The fraction of the gas which participates in star formation decreases nearly linearly with decreasing gas density \(\log \Sigma_H \sim -1.0\), two orders of magnitude below the usually assumed threshold for star formation, at least 5 per cent of the gas is observed to be forming stars. The average \(\Sigma_H\), for the pixels with \(\Sigma_H > 10^4\) \(\text{pc}^{-2}\) is \(\sim 17.3\) \(\text{M}_\odot\) \(\text{pc}^{-2}\), and the average \(\Sigma_{\text{SFR}}\) for these pixels is \(3.5 \times 10^{-3}\) \(\text{M}_\odot\) \(\text{yr}^{-1}\) \(\text{kpc}^{-2}\). Thus, even for the densest gas in dwarf galaxies, the star formation efficiency (i.e. \(\Sigma_{\text{SFR}}/\Sigma_{\text{gas}}\)) is hence \(\sim 2.0 \times 10^{-10}\) \(\text{yr}^{-1}\), about a factor of 2 lower than the typical value for spiral galaxies (Leroy et al. 2008).

### 3.2 Massive star formation

FUV emission is sensitive to the SFR of intermediate-mass (\(M \gtrsim 3\) \(\text{M}_\odot\)), relatively long lived (lifetime \(\sim 10^8\) \(\text{yr}\)) stars. H\textalpha\ emission, on the other hand, traces the instantaneous SFR of massive (\(M \gtrsim 17\) \(\text{M}_\odot\)), short-lived (lifetime \(\sim 10^7\) \(\text{yr}\)) stars. For our sample galaxies, we show in Fig. 4 the \(\Sigma_{\text{SFR}}\) as deduced from the FUV emission (\(\Sigma_{\text{FUV}}\)), as well as the H\textalpha\ emission (\(\Sigma_{\text{H}\alpha}\)) as a function of \(\Sigma_H\), at a resolution of 400 pc. (Note that pixels corresponding to the gas not taking part in star formation, that is, with negative or zero flux, are not included in this plot.) The best-fitting power laws to the H\textalpha\ data are given by

\[
\log \Sigma_{\text{H}\alpha} = (1.98 \pm 0.04) \log \Sigma_H - 4.60 \pm 0.05.
\]

As can be seen the \(\Sigma_{\text{SFR}}\) and \(\Sigma_{\text{FUV}}\) points overlap within the scatter (indicated by the vertical line). None the less, as a comparison between equations (5) and (3) shows, there is a significant difference (\(\sim 2\sigma\), where \(\sigma\) is the quadrature sum of the individual errors) in the slope of the two relationships, with the \(\Sigma_{\text{H}\alpha}\) relation being steeper.

Discrepancies between the SFRs deduced by these two tracers have been investigated earlier by several authors, including, for example, Meurer et al. (2009), Pflamm-Altenburg et al. (2009) and Lee et al. (2009a). A number of explanations for the two rates to diverge have been suggested.

1. The stochastic paucity of high-mass stars at low SFRs. This would make \(\Sigma_{\text{H}\alpha}\) at low SFRs lower than \(\Sigma_{\text{FUV}}\). For example, Lee et al. (2009a) show that for SFRs lower than \(\sim 10^{-2}\) \(\text{M}_\odot\) \(\text{yr}^{-1}\), the H\textalpha\ emission systematically underpredicts the true SFR.
2. Non-uniform SFRs. For example, if the star formation is bursty, then a few million years after the burst all the OB stars would have died and the H\textalpha\ emission would once again systematically underestimate the true SFR.
3. The leakage of ionizing photons, either out of the galaxy or into a more diffuse region of the interstellar medium, where the resulting H\textalpha\ emission has too low a surface brightness to be detected (e.g. Melena et al. 2009). Once again, this would result in the H\textalpha\ emission underestimating the true SFR.
4. Variations in the IMF. For example, Meurer et al. (2009) identify correlations between \(\Sigma_{\text{SFR}}\) and \(\Sigma_{\text{H}\alpha}\), and global galaxy parameters like the luminosity, rotational velocity and dynamical mass, and argue that this implies an IMF that varies with environment. Weidner & Kroupa (2005) present a model in which the underlying IMF is universal, but a dependence of the most massive star formed in a cluster on the mass of the cluster leads to the total stellar population having a steeper IMF than the canonical one.
5. Dust extinction. Since dust extinction is more at the shorter wavelengths, the undercorrection for dust would lead to the FUV emission underestimating the true SFR. Note that in most of the above scenarios, the H\textalpha\ emission would underpredict the true SFR.
One would expect \( \Sigma^{H\alpha}_{\text{SFR}} \) to exceed \( \Sigma^{\text{FUV}}_{\text{SFR}} \) (as observed for about half of our sample) only if (1) the IMF is more top heavy than assumed; or (2) the dust extinction has been underestimated.

To explore this issue further, we show in Fig. 5 pixel-by-pixel correlations of \( \Sigma^{H\alpha}_{\text{SFR}}/\Sigma^{\text{FUV}}_{\text{SFR}} \) (both at 150-pc resolution) with \( \Sigma_{\text{SFR}} \) and \( \Sigma_{H\alpha} \) (at 400-pc resolution). In each panel, the hollow squares are for those galaxies for which the global \( \Sigma^{H\alpha}_{\text{SFR}} \) is greater than the global \( \Sigma^{\text{FUV}}_{\text{SFR}} \), while the filled circles are for those galaxies for which the global \( \Sigma^{H\alpha}_{\text{SFR}} \) is less than the global \( \Sigma^{\text{FUV}}_{\text{SFR}} \). From panel (a), one can clearly see that the anticorrelation between \( \Sigma^{\text{FUV}}_{\text{SFR}}/\Sigma_{\text{SFR}} \) and \( \Sigma^{H\alpha}_{\text{SFR}} \) seen on global scales continues even on scales as small as 150 pc. The right-hand axis of the panels is the amount of differential dust obscuration required to bring the two SFR estimators into agreement. From Fig. 5, one can see that bringing the two SFR estimators into agreement at the lowest SFRs requires the dust obscuration to be more at H\( \alpha \) than at FUV, which is physically implausible. It is more likely that one of the several mechanisms discussed above for suppressing the H\( \alpha \) flux at low SFRs is operative. At high SFRs, where \( \Sigma^{H\alpha}_{\text{SFR}} > \Sigma^{\text{FUV}}_{\text{SFR}} \), the average \( \Sigma_{H\alpha}/\Sigma_{\text{SFR}} \) required to bring the two estimators into agreement is 8, that is, the gas should be about twice as dust rich as the Small Magellanic Cloud (SMC) (for which \( \Sigma_{H\alpha}/\Sigma_{\text{SFR}} \) is 16.3 from Bouchet et al. 1985). If one assumes that these regions have substantial molecular gas and that the galaxies follow the luminosity–metallicity relation for dwarfs (e.g. Ekta & Chengalur 2010) and that dust is proportional to metallicity, then the required molecular gas density to bring the gas-to-dust ratio to the same value as the SMC is \( \Sigma_{H\alpha} \gtrsim 10^5 M_\odot\text{pc}^{-2} \), similar to the peak density at the centre of spirals, which again seems unlikely. In summary, it does not appear that dust extinction is the primary cause of the disagreement between \( \Sigma^{H\alpha}_{\text{SFR}} \) and \( \Sigma^{\text{FUV}}_{\text{SFR}} \) at the high-\( \Sigma_{\text{SFR}} \) end.

In terms of direct observables, panel (b) shows that for the same amount of FUV emission, galaxies with lower global \( \Sigma^{H\alpha}_{\text{SFR}}/\Sigma^{\text{FUV}}_{\text{SFR}} \) are underproducing H\( \alpha \) emission. This could be either because the galaxies have a fading starburst or because the galaxies are not producing high-mass stars. Lee et al. (2009a,b) find that the frequency and amplitude of starbursts in dwarfs make the former explanation unlikely. However, a more detailed calculation, and observations of a larger sample, would be needed to properly settle this issue. The most striking feature of the plots, however, is in panel (c), which shows that galaxies with lower global \( \Sigma^{H\alpha}_{\text{SFR}}/\Sigma^{\text{FUV}}_{\text{SFR}} \) do not have gas with column density \( \gtrsim 10^4 M_\odot\text{yr}^{-1} \). The most straightforward interpretation of this is that massive star formation is more likely to happen in gas with high column density. Indeed, star formation models have supported such a correlation (e.g. Krumholz et al. 2010). While the linear scales that the models refer to are much smaller than those that we are dealing with here, such a correlation is likely, given that high-density star-forming regions are more likely to occur in regions where the overall gas density is higher.

## 4 CONCLUSIONS

We find a clear stochasticity between the SFR surface density and the gas column density. All gas with \( \Sigma_{H\alpha} \gtrsim 10^4 M_\odot\text{pc}^{-2} \) has associated star formation. While the fraction of star-forming gas decreases with decreasing \( \Sigma_{H\alpha} \), there is no sharp ‘threshold’ below which the star formation is completely quenched. We also find that galaxies for which disc averaged \( \Sigma^{\text{FUV}}_{\text{SFR}} < \Sigma^{H\alpha}_{\text{SFR}} \) are marked by the absence of high H\( \alpha \) column density (i.e. \( \Sigma_{H\alpha} > 10^5 M_\odot\text{pc}^{-2} \)). This is consistent with models in which the formation of high-mass stars preferentially happens in regions with high gas column density.

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