Chapter 4

Star Formation Analysis: The entire subsample

4.1 Methodology

After testing our method on two galaxies only we have carefully extended its use to our whole subsample. The gas surface density maps rely only on H I observations, as molecular gas observations are very scarce once we move into the low luminosity regime of dwarf galaxies. From the H I gas kinematics we have derived inclination estimates for most of the galaxies in our subsample. Galaxies such as DDO 155, DDO 165, M81dwA, DDO 75, DDO 187 and DDO 210 show no circular rotation, so the inclination could not be estimated in this way. For these galaxies we have used the inclination derived from ratio of the minor to major axis of each galaxy in the *V*–band (Hunter & Elmegreen, 2006). We apply the inclination correction to both the H I and the SFR surface density maps. To create our star formation rate maps we have used four different tracers based on FUV, Hα emissions and their combinations with 24μm emission. We extend our discussion on the efficiency of these tracers in the next section (see Section 4.1.1). We remind the reader that our subsample contains two galaxies (DDO 155 and DDO 165) not observed in FUV and two galaxies (M81dwA and DDO 210) showing no emission in Hα. Based on the findings presented in the previous chapter, we continue to apply no internal extinction correction when using tracers such as FUV and Hα on their own. We check however if the low level of internal extinction holds also for the other galaxies in our subsample and discuss our findings in Section 4.1.2. Apart from the just mentioned corrections, we do not apply any other corrections, leaving considerations regarding the shape of the galaxies, the H I flaring and the H I scale height for further refinement in future projects.

4.1.1 SF tracers

TBD

4.1.2 Internal Extinction

Just as we have already mentioned in the previous chapter, Section 3.2.2, we estimate the contribution of internal extinction to our SFR maps by comparing different star formation tracers and assessing what colour index value E(B-V) corresponds to the observed 24 μm emission. We remind the reader that at 24 μm we observe the obscured light, which ~~gets~~ is re–processed through dust and re–radiates at infrared wavelengths (Calzetti et al., 2007, 2010). Our method automatically implies a series of assumptions ~~such as~~: the extinction law used in deriving the colour index value E(B-V) from the estimated internal extinction correction is appropriate, the factors defining the amount of obscured and unobscured light (see Equation 3.3 and Equation 3.4) hold true also in the low metallicity environment of dwarfs, and finally the re–processed light radiates at the same infrared wavelength (24 μm) in both dwarfs and spirals.

In the previous chapter we ~~suspend our study once we can confidently~~ concluded that the weak 24 μm emission suggests low dust content and hence a more transparent medium where internal extinction is at such low levels that no correction is necessary. Here, however we would like to extend that study and take advantage of the larger sample available to us at this stage. For the interested reader, in Appendix B, Figure B.1 we present for each individual galaxy the comparison between SFR maps using FUV+24 μm as a tracer and FUV only as a tracer assuming both the Milky Way (right) and the SMC (left) extinction laws. In the figure, to ~~the attempt of~~ matching the 24 μm emission with the appropriate internal extinction correction, we use different colours for different colour index E(B-V) values, ranging between 0 and 0.05 mag. ~~and hold true~~ We look for the value that is closest to the 1:1 black continuous line in the figure. In Appendix B, Figure B.2 we proceed similarly, involving Hα and Hα+24 μm

Need to give basic differences

That is, we look for the extinction value that brings SFR determined from FUV+24 μm and SFR determined from FUV only into closest agreement.

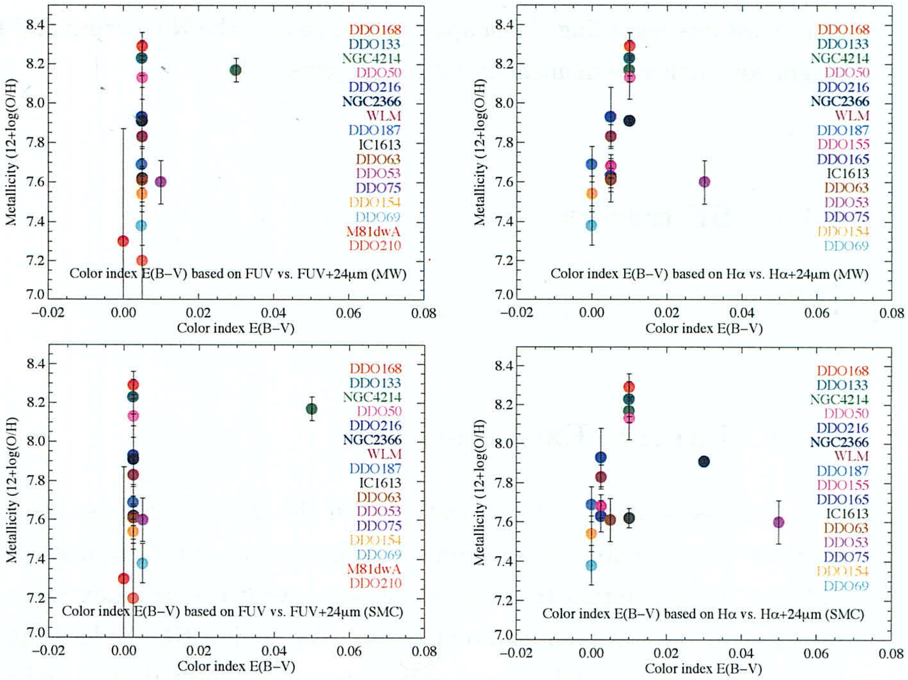


Figure 4.1: For all galaxies in our subsample with appropriate ancillary data available, we present the colour index E(B-V) as a function of metallicity. The colour index E(B-V) values have been inferred from comparing SFR from FUV only and FUV+24 μm (left) and SFR from Hα and Hα+24 μm (right) based on the Milky Way extinction law (top) and SMC extinction law (bottom).

a vertical line at 0 would be nice.

as SFR tracers.

The colour index E(B-V) values found in the above described manner are shown as a function of metallicity in Figure 4.1. This figure has four panels, each panel presenting colour index values derived from a unique combination of a SF tracer choice and an extinction law assumption. In general, no matter which of the four panels we examine we find that the colour index values are low, confirming our preliminary conclusion based on DDO 168 and DDO 133 alone, that no internal extinction correction is necessary. This is to be expected in the low metallicity regime, where the dust abundance is low as reflected by the weak 24 μm emission and hence the medium is more transparent. For the immediate requirements of our project this conclusion alone would be enough, however we cannot refrain from exploring this subject a little bit further.

At the beginning of this section we mentioned a few assumptions we made in our line of thought and now we have the opportunity to return to them and discuss what impact they in fact have on our results. In Figure 4.1 we differentiate based on the extinction law assumed (Milky way or SMC) and find that for FUV as a SF tracer, when assuming the SMC extinction law instead of the Milky Way one, the estimated colour index E(B-V) value doesn't change for 38% of our subsample and changes minimally, decreasing by ~~with~~ 0.0025 mag for 56% of them. The exception is DDO 53 with a decrease in estimated colour index E(B-V) value of 0.005 mag. If the SF tracer considered is Hα then we find no change in 31% of our subsample, minimal changes of 0.0025 mag lower values in 44% of our galaxies and three exceptions. While IC 1613 shows an increase of ~~with~~ 0.005 mag in the value of the estimated colour index value with the change of the extinction law assumption, NGC 4214 and DDO 53 present an increase of 0.02 mag. Overall, we can say that for both tracers the change in the extinction law assumed has a minimal impact on the estimated value of the internal extinction correction. ¶ What is surprising and difficult to explain is why for the three exceptions, the change in the extinction law assumption produces a decrease of the colour index value for FUV as SF tracer and in increase of the colour index value for Hα as a SF tracer. Such a behaviour, makes more obvious the fact that the colour index values found for FUV and Hα as SF tracers coincide only in four galaxies when assuming a Milky Way extinction law and in two galaxies when assuming the SMC extinction law. The culprit here may well be the choice of extinction law, in the sense that the case of SMC or the Milky Way might not be fully applicable to all other galaxies.

Essentially ∅ given the uncertainties!

Yes!

Could this have to do with the shape of the curves?

Good! But still well within oth uncertaintie

Another assumption mentioned above is that the amount of obscured and unobscured light does not change depending on environment. Such an assumption is not necessarily true. In the low luminosity galaxies, the infrared luminosity also decreases, because ~~such that~~ a larger portion of the light from recent star formation can reach us directly, without being obstructed by dust (Relaño et al., 2007; Calzetti et al., 2010). If not accounted for, the increasing medium transparency leads to underestimating the true star formation rate so the combining factors should be amended ~~accordingly~~. In our internal extinction estimating method we have used non-amended factors, but only after conducting a separate study where we found that if we amend the factors according to the Calzetti et al. (2010) recipe, by lowering the contribution of the 24 μm luminosity from 0.031 (see Equation 3.3) to 0.020, the value of the colour index value shows literally no change for FUV as a SF tracer and only a mild change on one out of sixteen galaxies when using Hα as a tracer.

Why under?

You mean t proportionalit used in combining?

from normal dusty conditions. In what sense — how should the proportionalities be changed up or down?

In the low luminosity regime, dust properties change (Rosenberg et al., 2008)

Ⓐ I remember at the begining extinction seemed an intractable problem, but you found a way to deal with it. Good job!!

Why are we now discussing 70 + 160 μm instead of 24 μm?

and infrared tracers such as 70 μm and 160 μm become unreliable (Calzetti et al., 2010), because the SF light is no longer fully traced by dust emission. In other words, the lower dust content of an increased transparency medium, while it simplifies matters by reducing the importance of internal extinction corrections, it also adds ~~in~~ complications due to the fact that the observed dust emission is more extensively contaminated by other (than star formation) dust heating processes (Calzetti et al., 2010). Such complications open up the subject of how reliably does 24 μm trace the obscured light in low dust content systems. As long as the extension of this particular tracer to the low luminosity regime, as suggested by Calzetti et al. (2010), involves no fundamental physical ~~conceptual~~ changes but rather the need of nonlinear calibrations to account for both the increased medium transparency and the lower effective dust temperature, we can still be confident that our method of estimating the internal extinction is valid in a relative sense. ~~safe from any ill assumptions.~~

Do you mean it may be off in an absolute sense, but relative is fine?

Finally, it is also important to notice in Fig. 4.1 that our estimated colour index values show no dependance on metallicity when FUV is the chosen SF tracer, but do show a mild dependance on metallicity when the SF tracer is Hα. Because of the very nature of our method the colour index value is also a dust abundance indicator. Therefore the relation between metallicity and the colour index values in our subsample could also be viewed as confirming that dust abundances are not proportional to metallicity as found by Galametz et al. (2011).

But they are as shown by Schruba et al 2012,

Ⓐ

4.2 Neutral Gas Mass, and Molecular Gas Mass Predictions

For ~~all~~ the galaxies in our subsample, all observed in H I with the VLA telescope, we calculated the H I mass (see Table 4.1). Also we collected from the literature ~~all~~ the available single dish measurements of the H I mass in our galaxies ~~of interest~~ and compared these values to the ones measured ~~calculated~~ by us. As shown in Table 4.1, in general we find good agreement between the single dish and our measured values.

Need to quantify, or refer to Hunter et al & leave this out. The important point is that most of the gas is in our maps! Maybe you should state that explicitly.

In the study of SF laws an important quantity is the gas surface density. In normal conditions, the gas surface density would sum ~~up~~ both the neutral and the molecular gas and account for the presence of Helium. However in the low metal-

← Normalization as in ↓ is necessary. Here the overall imprint is probably M_V or mass of galaxy vs O/H, with $M_{mole} \propto$ Mass of galaxy. Just a guess.

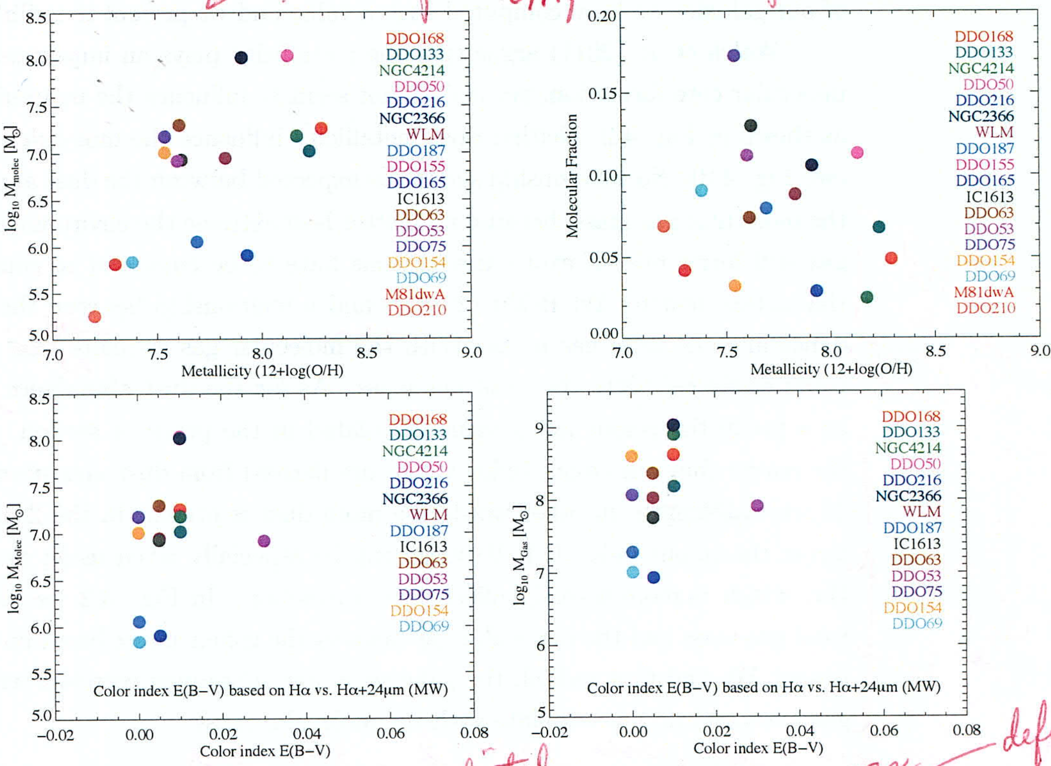


Figure 4.2: For all galaxies we plot the predicted molecular mass (top left) and molecular gas fraction (top right) against metallicity and also the molecular mass (bottom left) and the total gas mass (bottom right as a function of colour index E(B-V) value obtained using Hα as a SF tracer).

define

Take away points?

licity environment of dwarfs several complications prevent us from being able to measure the molecular gas quantity. Due to the low metallicity, the CO cores are smaller and underluminous (Bolatto et al., 2007), so we loose our only molecular gas tracer. Current lines of study use dust as a proxy for molecular gas measurements. However, since the discovery that the dust properties in dwarf galaxies are different than in spirals (Rosenberg et al., 2008), using dust as a tracer for molecular gas in dwarfs is a method that still needs refinement. Although we do not expect a large quantity of molecular gas in dwarf galaxies, an estimate of this quantity is very useful. We can use the SFR to provide ~~Since we cannot measure it, for the purpose of this project we were content to have~~ an upper limit ~~which can be predicted based on the SFR map.~~ As prescribed by Leroy et al. (2008), knowing that molecular gas and SFR surface densities are connected through a 1:1 relation and hence that the corresponding SFE is constant and equal to 5.25×10^{-10} yr^{-1}, one can ~~could~~ predict the molecular gas mass. For each

~~So sad too.~~

Why? Low absolute SFR? But molecul gas fraction perhaps mo important.

based on spirals?

State explicitly that this is H_2, the workhorse molecular mass, not just CO the trace molecule in the core. Correct?

I forget the intro now, but remind the reader that CO is a tracer for H_2 + use X_{CO} to estimate H_2 + X_{CO} comes from MW studies, + X_{CO} is going to be different at low metallicity. Just a quick reminder of the content.

of our galaxies we have computed such a value and we present it in Table 4.1.

Walch et al. (2011) argue that the metallicity plays an important role in the molecular core formation, yet it does not seem to influence the molecular gas mass as shown in Fig. 4.2. Neither does metallicity influence the molecular gas fraction (see Fig. 4.2). No relationship should be expected between the dust abundance and the molecular gas mass, because no matter how extreme the environment molecular gas still forms even if exotic mechanisms have to be employed to compensate for the metals dearth. Yet Bekki (2013) found a relationship between the dust abundance and the total gas mass. With ~~the~~ our molecular gas estimate and HI mass, ~~that~~ we have ~~we could easily calculate~~ the total gas mass. As for the dust abundance, we ~~will~~ use as a proxy the colour index value calculated in the previous section. We remind the reader that our colour index values are derived from dust measurements at ~~the~~ 24 μm ~~wavelength~~, in other words the more dust is present in the 24 μm map the larger the colour index E(B-V) value will be especially when using as a SF tracer Hα, which is more severely affected by extinction. In Fig. 4.2 we plot both the total gas mass and the molecular gas mass vs the colour index based on Hα as a SF tracer. We find that indeed, the galaxies in our subsample correlate with the total gas mass and do not correlate with the molecular mass.

a global dust/gas ratio?

But Krumholz argues for SF in HI sometimes. Do we have to have molecules? Interesting, but no answer.

The range in E(B-V) is so small that it is essentially constant. Isn't this more a density of dust than an absolute mass of dust? E(B-V) could remain constant but a galaxy could be bigger + bigger with total dust mass growing. If you could assume a dust/gas ratio and get Mdust but it is not very interesting here.

4.3 Neutral Gas and Stars vs. Star Formation Rate and relations therein in individual galaxies

One of the main results of the study on DDO 133 and DDO 168 presented in the previous chapter is the clear emergence of two relationships, one between SFR and H I surface densities and the other between SFR and *V*–band surface densities. Here we extend that study to a larger sample, a sample of 18 galaxies, DDO 133 and DDO 168 included. In Figures 4.3 to 4.20, we present for each galaxy in our subsample a composite of six panels where we explore the relationship between SFR (traced by both FUV only and Hα ~~only~~) and H I surface densities, between SFE and neutral gas surface density, between SFE and stellar surface density as traced by 3.6 μm emission and ~~between SFR(traced by both FUV only and Hα only) and~~ by *V*–band surface densities. In all panels of the plots, the error bars in both directions are shown in red, and in the top panels in blue we identify the upper limits. Each

in SFR? areas where there is gas but not FUV or Hα emission?

point in these plots represents a resolution element of 400 pc.

In all of the galaxies in our subsample we confirm the existence of a tight relationship between SFR and V–band surface densities a relation which will be more throughly discussed in ~~a section of its own (see~~ Section 4.7. If we further dis~~se~~criminate between SFR based on FUV and based on Hα, we find that in general the two tracers agree. However, six out of 14 galaxies observed in both FUV and Hα show larger scatter in the SFR vs. V–band surface densit~~ies~~y relationship when SFR is traced by Hα rather than FUV. The case of DDO 154 and DDO 69 also stand out as having a different slope in their relationship depending on the SF tracer used in creating the SFR map. Also exceptional is the case of DDO 50, where the SFR vs. V–band surface densities relationship ~~has~~ at the high SFR end of the ~~point~~ distribution split into two distinct and parallel groups of points. ~~While examining the relation between the star formation rate and stars if we change our viewing angle a little bit and~~ If we consider the the SFR per unit gas, in other words the star formation efficiency (SFE), in relation ~~with~~ to the stellar surface density as traced by 3.6 μm (see Leroy et al. (2008) and references therein for explanations on how the stellar map is derived), we find that the higher the stellar density the more efficient the star formation process in most of the galaxies in our sample. Exceptions are ~~making~~ DDO 133 and DDO 154, ~~who~~ which have large error bars inherited from a poorer quality 3.6 μm map, and DDO 187, M81dwA and DDO 210 where the relationship is difficult to probe due to the low number statistics. Also in the SFE vs. stellar surface density plot, DDO 50 stands out again with two distinct groups of points one following an ascending trend and the other showing a constant SFE.

~~I would move the beginning of 4.~~

Another very important relationship present in all the galaxies of the subsample is the relationship between SFR and H I surface densities, the denser the H I, the higher the SFR density. For each individual galaxy we plot this relationship using both the FUV and the Hα as SF tracers and find that in general the two tracers agree, yet the relationship relying on Hα as a SF tracer exhibits more scatter and samples only the high end of the relationship. In DDO 69 although we are dealing with a low number statistics case, from close examination of Fig. 4.18 we notice that the relationship as traced by Hα is following closely the 10 Gyr depletion line, whereas, when it is traced by FUV, it has a different ascending trend. With the exception of DDO 187, which suffering ~~of~~ from low number statistics ~~as mentioned above~~, ~~all~~ the galaxies in the subsample show increasing SFE with higher H I surface density.

~~Again to change perspective on~~ To facilitate comparison of the SFR and H I surface densities relationship in Figures 4.21, we plot for each galaxy in our sample the density contours at 10%,

Ⓑ Does this argue for ~~azimuthal~~ radial conditions setting the ability to form stars + hence SFR?

as given by the legend in the figure.

25%, 50%, 75% and 90% of the pixel by pixel distribution~~of the relationship at study overlaid with~~ The black points with coloured centres, ~~each point~~ representing the average in both the SFR and the H I surface densities direction within two concentric~~al~~ circles ~~at~~ one beam size apart. The coloured centres are a visual aid for distinguishing between the different radii in the galaxy. This format allows us to conclude that the radial profiles of the galaxies follow very closely their 2D point distribution. In other words, although we are talking about ~~dwarf~~ irregulars (galaxies) the difference between neighbouring resolution elements within the region to be averaged is not big enough to create a discrepancy between the trend of the points obtained in azimuthal averaging and the distribution of all points. Therefore, these radial profiles might be a better description of the ~~points~~ distribution of individual ~~2D regions~~ 400 pc regions than any linear or polynomial fit. We will come back to this idea ~~though~~ in the following section.

HI beam? Not sure what that means here in Σ HI.

In other words, the points are from azimuthal averages + the contours from collection of 400 pc regions? This is interesting: Ⓑ

The choice of the working resolution has been fully explained in the previous chapter so we will not return to this subject here. We will, however, mention that imposing a unique resolution element to ~~an~~ the entire subsample of ~~irregular~~ galaxies has ~~as direct~~ the consequence ~~the fact~~ that some galaxies ~~such as~~ (DDO 216, DDO 187, DDO 155, DDO 165, DDO 69, M81dwA and DDO 210) ~~will~~ end up being represented by less than 60 points. With such ~~a~~ low number # statistics one cannot draw any final conclusions in these galaxies. ~~Just like in the case of~~ as for DDO 133 and DDO 168, we ~~did~~ perform ed for each galaxy a linear regression using the ordinary least squares (OLS) Bisector method (Isobe et al., 1990) and found for the galaxies not affected by low number statistics, that the power law index ~~number~~ ranges from 1.4 ± 0.09 in DDO 187 to 2.4 ± 0.03 in DDO 50. The large range ~~able~~ needed to accommodate ~~most of the~~ our galaxies ~~in our subsample~~ suggests that the SFR and H I surface densities relationship is not a straight~~-~~forward one. Because stars form out of molecular gas, relating star formation to neutral gas even conceptually is ~~an~~ indirect ~~relation~~, which may very well explain both the scatter of the relationship and the ~~particularity~~ variations of this relationship in each galaxy. We ~~already~~ know that not all the neutral gas available is turned into molecular gas, so to strive for a direct relationship between H I gas and star formation, one would have to be able to differentiate between the neutral gas that will turn molecular and the one that does not. For this reason Warren et al. (2012) isolate the cold component of the neutral medium and find that, contrary to all expectations, the cold H I regions do not coincide with the H I overall distribution density peaks, which ~~are~~ most frequently coincident with current SF sites. The fact that this relationship exists in dwarfs and not in spiral galaxies, suggests that in low metallicity environments H I represents more than a reservoir for molecular

But that is what you are looking for, isn't it? This relationship sort of gives that.

Reference Young et al + de Blok + Walter too.

which?

I think this is science, not just data presentation + so should go in § 4.4.

gas formation; it might play an active role in enabling certain mechanisms designed to compensate for the diminished quantity of metals available to participate in the shielding process (Maloney & Wolfire, 1997; Pelupessy & Papadopoulos, 2009). One could imagine, that a dwarf galaxy caught in the act of turning its molecular gas into stars would shield its molecular cores in very dense envelopes of H I gas. These neutral gas envelopes may very well be the drivers of the SFR and H I surface densities relationship.

You mean PDR
or something
larger?.
There are man
references to
the large PDRs
See Madden
references.

4.4 Star Formation Law

The Star Formation law, relates the star formation rate and the gas density through a power law (Schmidt, 1959; Kennicutt, 1998). In the previous section we have shown that in each galaxy of our dwarf sample there exists a relationship between the SFR and the H I surface densit~~ies~~y. If this relationship would have the same characteristics in all galaxies studied, it could be passed as a SF law in the neutral gas regime. Already in the literature there are results suggesting ~~that an~~ a SF law in the neutral regime ~~is emerging~~ for low metallicity galaxies and the outskirts of spirals (Bigiel et al., 2010b, 2011).

Rather than comparing the relationship amongst galaxies like we have done in the previous section, another way of looking at the relationship within the whole sample is by allowing all independent points in all galaxies to participate in one plot. To make sure that the galaxies with a smaller number of ~~representative~~ points participate ~~to~~ in the plot with equal importance when constructing the total distribution we use weighting. In this way we obtain Figures ~~such as~~ Fig. 4.22, where we present colour density contours of the points distribution of SFR vs. H I surface densities, SFE vs. H I surface density and SFE vs. SFR surface density for both Hα and FUV as SF tracers. ~~The~~ Fig. 4.22 shows agreement between the relationships sampled with different SF tracers. We also find evidence for increasing SFE with increasing H I surface density as well as SFR surface density. From this perspective it also becomes clear that the SFR vs H I surface densities relationship holds for all the galaxies in the subsample. This relationship is not without scatter, most probably caused by the imperfect overlap between the point distributions of individual galaxies and the scatter of the relationships within each galaxy. To quantify the power law index number N which best describes the total distribution of points, we use linear regression, more specifically the ordinary least squares (OLS) Bisector

How?

SFE relationship
is weak mostly
a round blob.

What does
this mean?

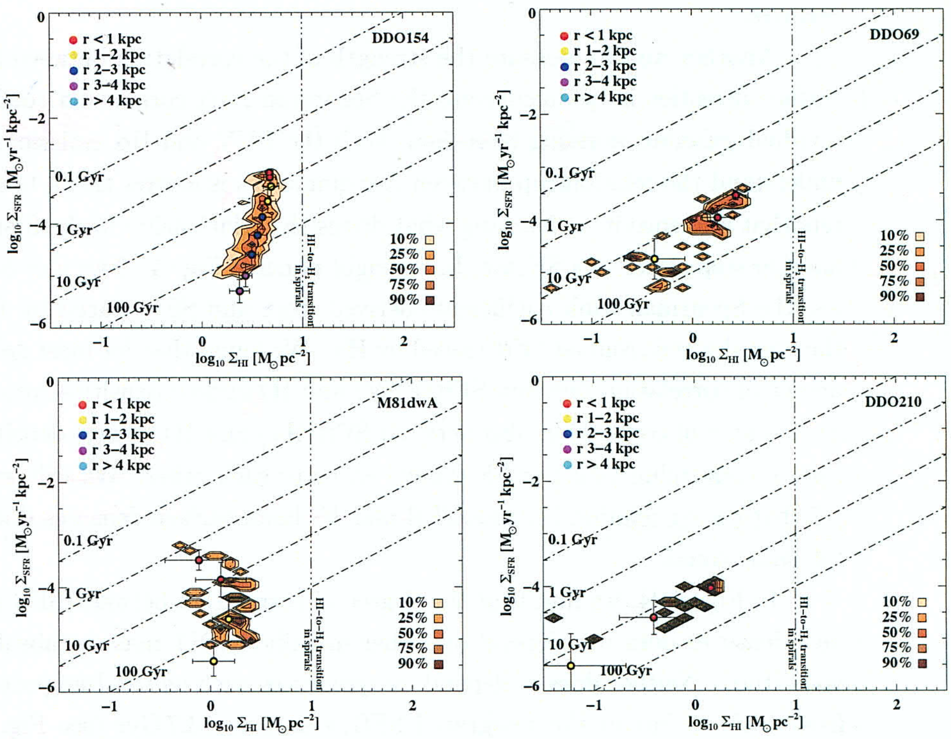


Fig. 4.21 continues ...

1,87±,02

$\Sigma_{SFR} \propto \Sigma_{HI}$

method (Isobe et al., 1990) and find for N a value of 1.87 ± 0.02. This value is very close to the value of 1.8 found for DDO 168 and DDO 133 in the previous chapter and also to the value of 1.7 found by Bigiel et al. (2010b) for a sample of five dwarf galaxies and the outskirts of 17 spiral galaxies. ~~For this total distribution of points~~ We also compute ~~the~~ a Spearman rank correlation coefficient of 0.67, indicating a high degree of correlation among the points of the distribution.

If we would like to do a more careful job of describing the point distribution in each galaxy and comparing them to achieve a more general SF law, one should be ready to admit that the relationship between the SFR and the H I surface densities in the log-log parameter space is not necessarily linear, as illustrated in Fig. 4.21. ~~If walking in the direction of~~ To find~~ing~~ the best functional form to describe the relationship in individual galaxies and from there achieve a unique SF law, ~~than~~ the most useful tool at hand may very well be the radial profile we've shown in the previous section. In the left panel of Fig. 4.23 we show in one plot all the radial profiles of all the galaxies in our subsample with FUV observations. We find a fair amount of overlap between the radial profile trends of different galaxies. However, it also becomes obvious that linear fits cannot fully describe these galaxies ~~and their~~

Describe what you see.

Why?

Some galaxies deviate from the overall trend: Why are DDO154 and M81dwA (?) similar to each other & different from the rest. Why does NGC 2366 (?) turn to the left at the top end? [You don't have to have an answer, but point out that interesting clues are held by the galaxy-to-galaxy variations?]

This is very interesting. We ~~ne~~ ~~[illegible]~~ ~~need~~ need to think of what else we can do with this.

~~features.~~

Another way to measure the strength of the correlation between SFR and H I surface densities is by calculating the Spearman rank correlation coefficient in individual galaxies, ~~deriving SFR from~~ for both the FUV SFRs and Hα ~~emissions~~. To better understand the relationship between two quantities it is ~~always~~ useful to find parameters that influence it, so learning what drives the relationship in the first place is yet another step closer to a SF law. In the right panel of Fig. 4.23 we plot for~~a~~ all galaxies, the Spearman rank coefficients derived from and SFR traced by FUV against the ones derived from an SFR traced by Hα. We found that for most galaxies a high degree of correlation between SFR(FUV) and H I surface densities corresponds to a high degree of correlation also between SFR(Hα) and H I surface densities, another way of confirming that our SF tracers agree to each other. ~~We will see in Section 4.7 that the correlation between SFR and $V-$band surface densities does not follow the same trend.~~

What I see is that the strength of the Hα correlation is weaker than that of FUV. Is that just that Hα doesn't go as far out, or as deep, or is rather for any reason? ~~[illegible]~~ Maybe the timescales is the main reason.

In Fig. 4.24, we find that the degree of correlation between SFR and H I surface densities does not depend on either metallicity, H I mass or absolute V–band magnitude. Neither does it depend on quantities such as the Integrated SFR/area from FUV or Hα or the Integrated SFR/area over 13.7 Gyr (see Fig. 4.25). Although not shown here, we should mention that the correlation is not driven by the molecular or neutral gas fractions either.

4.5 The H I to H_2 Transition

In the previous chapter we looked at DDO 168 and DDO 133 and their H I to H_2 transition threshold and found that, although they have similar metallicities, they exhibit contradictory behaviours. While DDO 168 has an ~~the~~ H I maxim~~a~~um of 28 ~~27.7~~ $M_\odot$ pc^{-2}, DDO 133 has a maximum less than 10 $M_\odot$ pc^{-2}. ~~From the information provided by the two dwarfs in our case study in the previous chapter we~~ We concluded that metallicity alone ~~cannot~~ could not explain the H I maxima. We come back to this idea, here and involve our whole subsample ~~in the attempt to explain why in some dwarfs the 10 $M_\odot$ pc^{-2} limit found by Bigiel et al. (2008) for spirals does not continue to hold.~~ to see what the HI limits are in dwarfs, for dwarfs

From the 18 galaxies in our subsample, the following 8 galaxies ~~cross the~~ have HI maxima that are greater than the 10 M⊙/pc² ~~above mentioned~~ limit seen in spirals (Bigiel et al 2008): DDO 187, DDO 50, DDO 63, DDO 53, DDO 75, NGC 2366, NGC 4214, and DDO 168. We expected ~~this feature~~ the maxima to be correlated with the metallicity of the galaxies involved. Metallicity affects the transition from neutral to

Given that dwarfs are < solar metallicity, we would expect all dwarfs to have maxima > 10. But you only see 8 of 18. Isn't that strange? It must be telling us something interesting, unless it is a distance (beam smearing) affect, but by using 400 pc cells for all galaxies, it shouldn't be that.

Can you here put an average with big black dots of those that are similar and find some function that describes it — a polynomial?

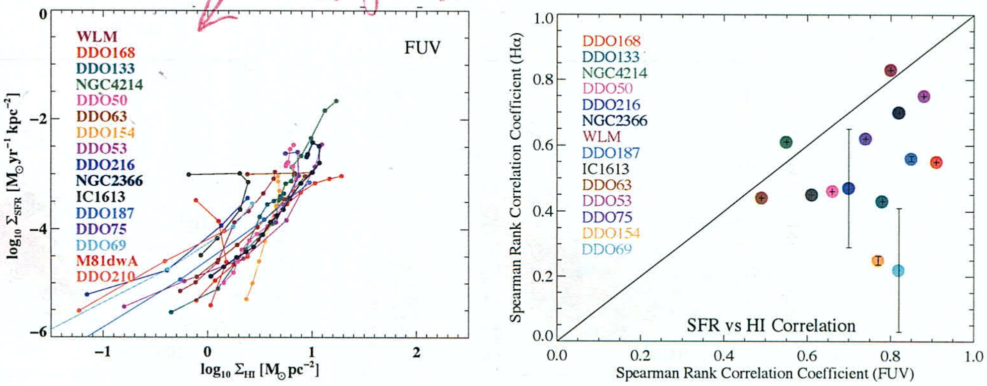


Figure 4.23: Left: For all galaxies that have both FUV and Hα observations we show the spearman rank correlation between H I surface density and SFR based on FUV (the x axis) and on Hα (the y axis). Right: For all galaxies in our subsample we compute the radial profiles in both the SFR (based on FUV only) and the H I surface densities maps, each point representing an azimuthal average inside two concentrical circles at a beam size distance of each other.

molecular gas in two ways: first, due to the metals deficit, the CO emitting cores ~~will~~ diminish and, second, self–shielding will ~~be~~ dominat~~ing~~e over dust–shielding (Bolatto et al., 2008). In other words, in low metallicity systems, the molecular phase can be described as small CO emitting cores (Madden et al., 1997) embedded in molecular clumps of similar size to the ones found in spiral galaxies, sitting in a dense H I envelope. The neutral gas in the H I envelope will not turn molecular because the interstellar radiation field (IRSF) will not allow it to cool, but it may act as a cushioning region, complementing the H_2 self-shielding necessary so that the newly formed molecules are not broken up into atoms by the stellar UV light. Therefore, the theoretical prediction is that, as metallicity goes down and dust–shielding lo~~o~~ses its dominating role, we will tend to see more dense H I envelopes, where the gas has the density necessary to turn molecular, but cannot cool due to the ISRF. ↑ define

And indeed, we see that almost half of our low metallicity subsample shows indications of denser H I envelopes. However, if we plot in the left panel of Fig. 4.26 the H I surface density maxima against metallicity, the expected trend ~~is~~ does not clea~~r~~nly emerg~~ing~~e. In galaxies with a metallicity 12+log(O/H) smaller than 8.0 and larger than 7.4, we find that as metallicity goes down the H I maxima goes higher, just as predicted by theory (Krumholz et al., 2009, 2011). Even so, the relationship is not clear; on one hand we have NGC 2366 which has the highest H I maxima in the group but rather a high metallicity and on the other hand there are galaxies

than?

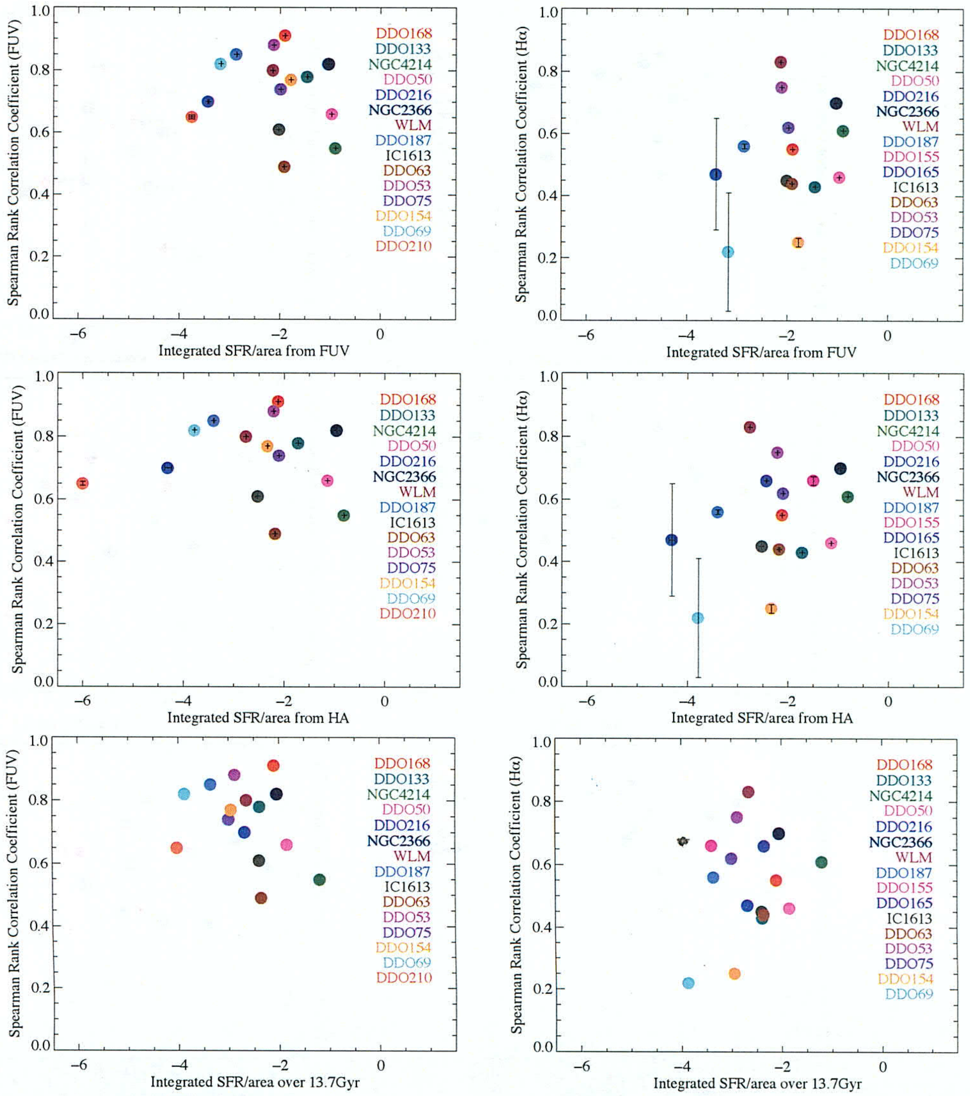


Figure 4.25: For all galaxies in our subsample, we plot the Spearman correlation coefficient between SFR surface density and H Isurface density vs. Log of the integrated SFR over area from FUV (top) and Hα (middle) and Log of the integrated SFR /area over 13.7 Gyr (bottom), plotted separately for two different SF tracers FUV (left) and Hα (right).

Is this just the first row / 13.7 Gyr?. Not sure that this is independent information.

Line at 10 would be useful.

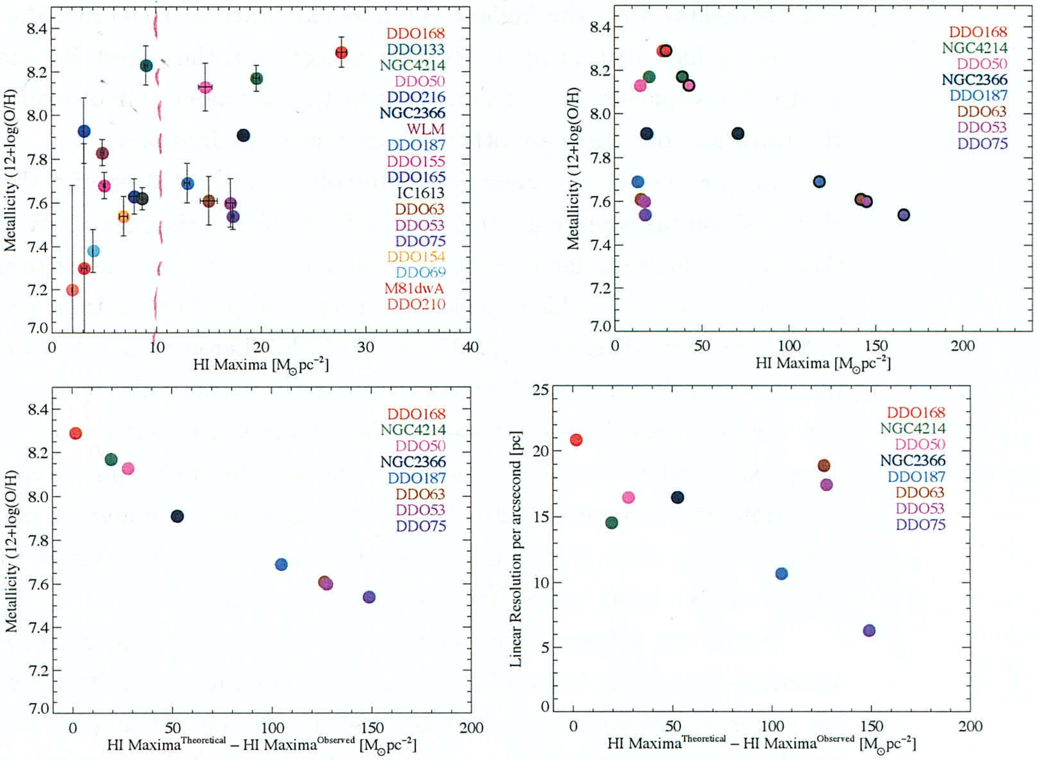


Figure 4.26: Top Left: For all galaxies we plot the H I maxima against metallicity. Top Right: For all galaxies that have H I maxima higher then 10 M$_\odot$ pc^{-2} we plot both observed values (coloured filled circles) and theoretical values based on Krumholz et al. (2011) assuming a clumping factor equal to 1 (black contoured coloured filled circles) against metallicity. We also show the difference between the theoretically predicted value of the H I maxima and the observed one as a function of metallicity (bottom left) and linear resolution per arcsecond (bottom right). Different colours represent different galaxies.

circles with black outline? Hard to ~~see~~ distinguish. Maybe line for theory + points for obs?

like DDO 155, DD 165, DDO 154 and IC 1613 with similar metallicities as DDO 187, DDO 63, DDO 53 and DDO 75, yet not going beyond the 10 M$_\odot$ pc^{-2} threshold. Also, if we do not discriminate based on a metallicity range, the number of outliers increases. The behaviour of galaxies like DDO 210, DDO 69 and M81dwA should not be entirely attributed to large error bars in the metallicity measurement, but one should note that all three galaxies seemed to have ceased their SF activity. They are known to have gone through SF episodes in the past, hence the FUV emission present in these galaxies, yet from the lack of Hα emission in DDO 210 and M81dwA and the deficit of Hα emission in DDO69, they have not formed stars in the past 10 Myr. The galaxies with a metallicity 12+log(O/H) larger than 8.0 are also in a league of their own, where the galaxy with the highest metallicity, DDO 168 is

This is very interesting.

also the galaxy with the highest H I maxima, whereas DDO 133, the galaxy with a similarly high metallicity is also the galaxy with the lowest H I maxima of the group. Consequently, we conclude that metallicity alone cannot explain the H I to H_2 transition, but there are other factors that come into play.

For low metallicity galaxies, Krumholz et al. (2011) predict that the H I to H_2 transition takes place at $10\,M_\odot\,pc^{-2}/cZ$, where Z is the metallicity and c is what they call a clumping factor ranging from 1 to 5 at resolutions of several hundred parsecs. In an article which applies the theoretical predictions from Krumholz et al. (2009) and Krumholz et al. (2011) in the SMC, Leroy et al. (2011) explains that the clumping factor c can be defined as a ratio between the molecular complexes and the gas surface densities~~. and~~ The larger the spatial scale the more the molecular complexes become unresolved and hence the need for a clumping factor larger than one. However, Leroy et al. (2011) find~~s~~ that changing the clumping parameter does not match the effect of smoothing and explains it as due to a larger than expected part of the H I being locked up as a warm, diffuse component.

This should be presented at the beg of this section & then come back to discuss c here.

densities or scales?

so not a resolution issue, but physical ISM differences between galaxies?

For all the galaxies in our sample we have calculated the H I to H_2 turnover, assuming a clumping factor of 1. At our linear resolution of 400 pc, a higher clumping factor ~~was~~ would be recommended, but because the change in clumping factor does not match the effect of smoothing ~~anyway~~ in the SMC and because ~~of the difficulty in choosing a certain value over another~~ of the lack of observational constraints on c, we left this value at 1, hoping that from our comparisons with the real data we could further refine this value. In the top right panel of Fig. 4.26 in the same parameter space as a function of metallicity we plot both the predicted H I maxima and the observed one and find a large discrepancy between points, the only close match being DDO 168. In the bottom panels of the same Fig. 4.26 we plot the difference between the predicted and the observed maximums against metallicity and linear resolution per arcsecond and find that the discrepancy between the theoretically predicted value and the observed one is metallicity dependent and not conclusively dependent on resolution. We would have expected a dependence on resolution that would have brought us back to our unorthodox choice of clumping factor, yet we found that the lower the metallicity the higher the discrepancy between the predicted and the observed values of maximum. Clearly metallicity plays an important role in driving the H I to H_2 ~~turnover~~ transition, however it seems to act in complicity with some other hidden parameter which is neither the clumping nor the resolution.

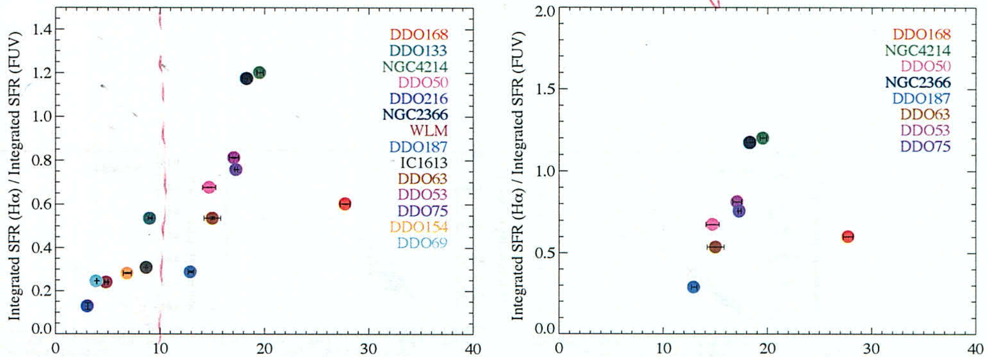
I don't see this. Need better way to plot.

I see a relationship with resolution. Maybe need theo/obs instead of theo-obs because ratio gives c. Same for metallicity.

Oh.

Using a sample of 23 dwarf galaxies, Roychowdhury et al. (2011) found that

I don't see the need for this plot. Contained in left.



?

Figure 4.28: Left: For those same galaxies we plot the H I maxima as a function of the ratio of the integrated star formation rates based on Hα and on FUV. Right: For those galaxies that have H I maxima higher then 10 M$_\odot$ pc^{-2} we plot the H I maxima as a function of the ratio of the integrated star formation rates based on Hα and on FUV. Different colours represent different galaxies.

So Hα is predicting more SF than FUV?

the H I to H$_2$ transition above the 10 M$_\odot$ pc^{-2} threshold always happens in galaxies where the ratio between the SFR surface density based on Hα as a SF tracer and the SFR surface density based on FUV as a SF tracer is higher than 1. To test their results in our own sample, in Fig. 4.27 we plot the SFR surface density based on FUV vs the SFR surface density based on Hα and highlight in orange all the points that have an H I surface density higher than 10 M$_\odot$ pc^{-2}. Out of the eight galaxies that have some orange points, in four of them (DDO 168, DDO 63, DDO 53 and DDO 75) the orange points are associated with SFR(Hα) and SFR(FUV) surface densities ratios of one, whereas in three of them NGC4214, DDO 50 and NGC 2366 the ratio of each orange point is above one as predicted by Roychowdhury et al. (2011). Finally, in the case of DDO 187 the orange points have a ratio smaller than one.

Wow. They are very different.

Good.

Instead of working with surface densities ratios we tested the relation with more global values such as integrated SFR. In the right panel of Fig. 4.28 we plot the ratio between the integrated SFR based on Hα and the one based on FUV against the H I maxima and find a good correlation between the two quantities. Although the value of the ratio has a different value locally than globally, with the exception of DDO 50, all other galaxies preserve their order in the plot, proving that both ratios from global values and from surface densities relate with the H I maxima.

Interesting, but I can't imagine why.

I don't follow this!

This relationship could be explained if we view the ratio as an indicator of how close in time the SF episode really is and take into account that the dense H I envelopes ~~due to which the H I maxima is above 10 M$_\odot$ pc^{-2}~~ whose HI densities we seek have short lifetimes and

The variations in SF amplitude with time?

One might expect Hα/FUV to vary in a SFing region with time. Obviously, when it is old, you have 0/FUV and when it is young you might have Hα/little visible FUV.

Very interesting idea.

Because FUV averages over 200 Myr which is long compared to HI cloud lifetime, or CO

are only observable close to the time of the SF episode. Consequently, depending on how much time has passed since the SF episode, or how close the next episode is the H I maxima will change and may not always represent the high density achieved in the envelope when the H I to H_2 transition actually happens. This scenario may also explain why similar metallicity galaxies have very different H I maxim~~ums~~a. ~~Also in the right panel of Fig. 4.28, among all the galaxies plotted~~ There is a surprising outlier, DDO 168 the galaxy which matched so closely the theoretical predicted value for the H I maxima does not follow the main trend, its ratio between the integrated SFR based on Hα and the one based on FUV is lower than what the trend would predict for such a high value of the H I maxima. Could it be that what sets DDO 168 apart is that among all the galaxies in the sample it is the only one about to start a new SF episode, rather than recently having gone through one?

FUV is higher than Hα. FUV should last longer than Hα.

~~4.6 Multiple Components in the SF Law~~

~~TBD~~ ~~whatever~~ Isn't this contained in §4.4, page 138?

4.7 The Correlation between SFR and the Stars

We have already established in Section 4.3 that for all the galaxies in our sample the SFR and V–band surface densities ~~are in a~~ correlate tightly ~~relationship~~. This result not only holds in dwarf galaxies at the higher end of our metallicity range such as DDO 168 and DDO 133 (see previous chapter), but also holds for all galaxies in our sample confirming the existence of the the SFR and V–band surface densities relationship at small scales (at least 400 pc resolution element). This ~~very~~ relationship but at larger scales (per galaxy) has been previously established by Hunter et al. (1998)~~;~~ and Hunter & Elmegreen (2004). The fact that this relation holds locally as well as globally, suggests that current stars play an active role in star formation. Defining and understanding the exact role that stars play int~~o~~ the star formation process is a puzzle yet unsolved. As mentioned in the previous chapter, their role might be to induce star formation (Dopita et al., 1985; Brinks et al., 1990; Dolphin & Hunter, 1998)~~,~~. ~~h~~However, ~~it may~~ their role might also be to enable the molecular gas formation by driving up the midplane pressure (Leroy et al., 2005).

I like this pressure idea.

To analyse this relationship better, in Fig. 4.29 we ~~change our perspective and~~ look at density contours at 10%, 25%, 50%, 75% and 90% of the pixel by pixel distribution of FUV SFR ~~based on FUV only~~ surface density vs. V–band surface density overlaid with the radial profile of this distribution (black points with coloured circles). Each black point represents the average value from within two concentrical circles at a distance of one beam size of each other and at a certain radius from the centre of the galaxy. The coloured cores of the black points are meant to help the reader asses at any time the corresponding galactocentric radius each particular point corresponds to. The radial profiles follow the pixel by pixel distribution very closely, except in DDO168, which means that within the averaging region resulting in one black point of the radial profile, the contributing pixels have similar values, nor too high nor too low from the average. As with the ~~Following the same line of thought like in the~~ SFR ~~based on FUV only surface density vs.~~ H I surface density relationship, the radial profiles are a better fit to our data than any other linear or polynomial fit. Therefore in Fig. 4.30 we show ~~all~~ the radial profiles of all the galaxies in our sample with FUV data, each galaxy plotted with a different colour. In this exercise we find there is reasonable overlap between the different galaxies, but there are also galaxies such as DDO 216, DDO 75 and DDO 50 that lie distinctively away from the main conglomeration of profiles.

annuli are 1 HI beam width wide?

In other words azimuthally averaged annuli?

Overall relationship? Can you give a relationship?

In what way? Different slope, offset up, offset laterally?

In the attempt to better understand the nature of this relationship between SFR and V–band surface densities, we computed for each galaxy in our sample the Spearman rank correlation coefficient, an indicator of ~~how strong~~ the strength of the correlation between the two quantities ~~really is~~. We computed these Spearman rank correlation coefficients for SFR based on FUV and Hα and in Fig. 4.30 we compare the two sets and find that a high degree of correlation between SFR(FUV) and V–band surface densities does not necessarily imply a high degree of correlation between SFR(Hα) and V–band surface densities. The fact that there are galaxies with high degree of correlation between both SFR(FUV) and SFR(Hα) and V–band surface densities shows that the relationship SFR vs. V–band is not driven by similar star populations emitting in both V–band and FUV. Further in Fig. 4.31 we plot separately the above mentioned sets of correlation coefficients against quantities like metallicity, H I mass and absolute V–band magnitude and find that the degree of correlation between SFR and V–band surface densities is independent of any of the latter mentioned quantities. In Fig. 4.32 we plot the correlation coefficients against integrated SFR from FUV over area, integrated SFR from Hα over area and integrated SFR/area over 13.7 Gyr and find no dependence on integrated SFR/area of the correlation co-

But Hα could come + go. Is this a timescale issue again?

What would happen if you bypass SFR + plot μ_V vs Σ_{HI} for the galaxies?

efficients based on FUV as SF tracer and a very mild dependance with considerable scatter of the correlation coefficients based on Hα.

Rather than looking at individual galaxies, we can also make a unique plot where all the independent points of each galaxy contribute to a total distribution of points. As we mentioned in Section 4.3 some of the galaxies in our subsample due to their small size and distance from us, at 400 pc linear resolution are represented by a small number of points(under 60), therefore when plotting the total distribution of points the small galaxies contribution would be lost in the sea of points coming from larger galaxies. To avoid this, in Fig. 4.33, we plot the density contours of a per galaxy weighted total distribution of points. Just as the misalignment of the radial profiles was suggesting in Fig. 4.30, the bottom panels of Fig. 4.33, the shredded density contours of the SFR vs. V–band surface densities point distribution is the effect of the imperfect overlap of some contributing galaxies and the weighting which forced all contributing points from all galaxies to have equal importance. We also show in Fig. 4.33 that as a whole our subsample presents an increasing SFR surface density and only a mildly increasing SFE with increasing stellar surface density.

How?

We are not able to explain how are these two quantities, the SFR and V–band surface densities exactly related and what parameter drives the higher degree of correlation in some galaxies rather than in others. Yet we are able to confirm the existence of this correlation at small scales and we suggest that although very close to linear this relationship is best described with radial profiles.

There's a lot of really cool stuff here, ~~sadly~~ intriguingly unexplained. We need to figure out where to go from here to figure it out.