The HI - Star Formation Connection: Open Questions

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Abstract. We show data from the Survey of Ionization in Neutral Gas Galaxies (SINGG) and Survey of Ultraviolet emission in Neutral Gas Galaxies (SUNGG) which survey the star formation properties of HI selected galaxies as traced by Hα and ultraviolet emission, respectively. The correlations found demonstrate a strong relationship between the neutral ISM, young massive stars, and the evolved stellar populations. For example the correlation between R band surface brightness and the HI cycling time is tighter than the Kennicutt-Schmidt Star Formation Law. Other scaling relations from SINGG give strong direct confirmation of the downsizing scenario: low mass galaxies are more gaseous and less evolved into stars than high mass galaxies. There are strong variations in the Hα to UV flux ratios within and between galaxies. The only plausible explanations for this result are that either the escape fraction of ionizing photons or the upper end of the IMF varies with galaxy mass. We argue for the latter interpretation, although either result has major implications for astrophysics. A detailed dissection of the massive star content in the extended HI disk of NGC 2915 provides a consistent picture of continuing star formation with a truncated or steep IMF, while other GALEX results indicate that star formation edges seen in Hα are not always apparent in the UV. These and other recent results settle some old questions but open many new questions about star formation and its relation to the ISM.

Keywords: Nearby Galaxies, Gaseous Disks, HI content, Star Formation, Surveys, Initial Mass Function, H Alpha, UV

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INTRODUCTION

Strong correlations between the star formation rate (SFR) of galaxies and their HI content have been known for some time. For example Kennicutt (1998a) showed that globally averaged star formation intensity, $\Sigma_{SFR}$, in galaxies correlates more strongly with the HI than with the CO surface density. This is puzzling since stars form out of the molecular not the neutral interstellar medium (ISM).

We are working on two surveys meant, in part, to examine the nature of the HI - star formation connection: the Survey of Ionization in Neutral Gas Galaxies (SINGG), and the Survey of Ultraviolet emission in Neutral Gas Galaxies (SUNGG). These image nearby galaxies selected blind to optical properties from the HI Parkes All Sky Survey (HiPASS) in the light of two star formation tracers: Hα (SINGG) and the far and near ultraviolet (FUV and NUV) continuum (SUNGG). Hα emission traces the presence of ionizing O stars having masses $M_\star \gtrsim 20 M_\odot$, while UV emission is sensitive to both O and B stars having masses down to $M_\star \gtrsim 3 M_\odot$. Meurer et al. (2006) discuss the SINGG observations and measurements. An initial description of the SUNGG survey can be found in Wong (2007). The full description of SUNGG is currently being written.
by Wong et al. while the preliminary results presented here are being written-up by Meurer et al.; both should be submitted for publication by the middle of 2008.

Some of the open questions we aimed to address with these surveys include What is the best form of the Star formation Law (SFL)? Is it constant? Is the Initial Mass Function (IMF) universal? What is the heating source for the HI dominated disks that are often seen to extend well past the apparent optical extent of galaxies.

There have been many papers on the SFL. Probably the most influential have been the papers of Kennicutt and collaborators (Kennicutt, 1989; Kennicutt 1998a, Martin & Kennicutt 2001). They show that the \( \Sigma_{\text{SFR}} \) has a power law dependence on the total ISM surface density \( \Sigma_{\text{gas}} \) where \( N \approx 1.4 \), but only where the \( \Sigma_{\text{gas}} \) is large enough for the ISM disk to be self-gravitating. Thus extended HI disks are thought to result if the ISM is not dense enough to form stars. The standard assumption in much of astronomy is that the IMF is constant, which certainly seems to hold for stars clusters (Kroupa, 2001). By using two star formation tracers we can test this assumption and probe whether the same SFL that holds for O stars also works for B stars.

The parameters derived from the SINGG and SUNGG data discussed here are based on integrated fluxes measured from concentric elliptical apertures. In particular, \( \Sigma_{\text{SFR}} \) and the R band surface brightness \( \Sigma_{\text{R}} \) are measured within the half-light radius and corrected for inclination. The gas cycling time \( t_{\text{gas}} \) is derived from the ratio of the HI and H\( \alpha \) fluxes with a crude uniform correction for helium and molecular gas. Star formation rates are calculated using the calibrations of Kennicutt (1998b) which adopt a Salpeter (1955) IMF over the mass range of 0.1 to 100 \( \mathcal{M}_\odot \). The SINGG data are corrected for dust absorption (and [N II] contamination) using the relationships of Helmboldt et al. (2004) and validated with FIR data as shown by Meurer et al. (2006). Dust absorption is removed from the UV fluxes based on the FUV – NUV colors (similar to Gil de Paz et al. 2007, for example).

### SCALING RELATIONS AND THE STAR FORMATION LAW

Our surveys do not have the data necessary to fully recalibrate the SFL. Instead we consider global properties and look for correlations, or scaling relations. These amount to “projections” of the SFL. As a baseline for comparison, we fitted the disk averaged measurements (ignoring central starbursts) from Kennicutt (1998a) to find a correlation coefficient \( r_{xy} = 0.60 \) and \( N = 1.4 \) for the correlation between \( \Sigma_{\text{HI}} \) and \( \Sigma_{\text{SFR}} \), with rms scatters in the residuals, \( \sigma \), of 0.40 dex in \( \Sigma_{\text{SFR}} \). The combined SINGG and HiPASS data allows us to recover the \( \Sigma_{\text{SFR}} \) versus \( \Sigma_{\text{HI}} \) correlation using a “pseudo” HI surface density \( \propto F_{\text{HI}}/(\pi r_{90}^2) \), where \( F_{\text{HI}} \) is the HI line flux, and \( r_{90} \) is the radius containing 90\% of the H\( \alpha \) flux. Our correlation has \( r_{xy} = 0.59 \), \( N = 1.66 \), and \( \sigma = 0.50 \) dex in \( \Sigma_{\text{SFR}} \). Hence using a pseudo-\( \Sigma_{\text{HI}} \) we recover a relationship very similar to the Kennicutt SFL.

We find other strong correlations between parameters characterizing star formation and the HI and stellar content of the targets. Figure 1a shows a nearly linear correlation (slope \( \alpha = 1.08 \pm 0.03 \)) between the H\( \alpha \) and R band intensity. This relationship is tighter than the Kennicutt SFL and our \( \Sigma_{\text{SFR}} \) versus pseudo-\( \Sigma_{\text{HI}} \) relation discussed above. Here \( r_{xy} = 0.75 \) and the \( \sigma = 0.29 \) dex. The average H\( \alpha \) equivalent width is 11Å, while the R band filter width is \(~1500\)Å, hence H\( \alpha \) does not significantly contaminate the R band
and the strong correlation is not spurious. This implies that the older stellar populations play at least as an important role in regulating star formation as does the H\textsubscript{I} content. A similar result was reported by Dopita & Ryder (1994). Note the many outliers above the correlation, these correspond to starburst systems. An even tighter (anti-) correlation, with fewer outliers, exists between $t_{\text{gas}}$ and $\Sigma_R$ as shown in Fig. 1b. Here $r_{xy} = -0.77$ and $\sigma = 0.28$ dex. Using this correlation “in reverse” one can estimate the H\textsubscript{I} content of galaxies to better than a factor of 2 from $R$ and H\textsubscript{\alpha} measurements.

Figure 2 shows the luminosity - surface brightness relationship of our sample. In panel (a) the $R$ band relationship is shown. Here $r_{xy} = 0.76$ and $\alpha = 0.40 \pm 0.02$, $0.53 \pm 0.02$ for ordinary least squares fit of Y on X and bisector methods, respectively. Fitting of the former type is displayed here because it works better when the correlation is weak as in panel (b). The bisector results agree very well with results found using over $10^5$ galaxies from the Sloan Digital Sky Survey by Kauffmann et al. (2003). In terms of stellar mass $M_{\star}$ and mass density $\Sigma_{\star}$ they find $\Sigma_{\star} \propto M_{\star}^{0.54 \pm 0.03}$, with $\sigma \approx 0.2$ dex, considerably tighter than our relationship which has $\sigma = 0.36$ dex. However, we can trace the correlation to fainter intensities using the SINGG data because our results do not require optical spectroscopy (see the dot-dashed line in Fig. 2).

In H\textsubscript{\alpha}, the luminosity - surface brightness correlation is weaker and shallower than in the $R$ band as shown in Fig. 2b. Here $r_{xy} = 0.38$, $\alpha = 0.27 \pm 0.03$ and $\sigma = 0.51$ dex, again with high surface brightness starburst outliers apparent. The relative shallowness of the correlation when using H\textsubscript{\alpha} is consistent with the expectations of the “down-sizing” scenario (Cowie 1996); relative to the stars already in place the star formation activity is stronger for lower luminosity systems. Stronger evidence of downsizing in the SINGG sample was presented by Hanish et al. (2006) who show that H\textsubscript{I} contributes a larger fraction of the dynamical mass than stars for low mass galaxies, while the situation is reversed for high mass galaxies. Low mass galaxies are less evolved because they have converted less of their ISM into stars than high mass galaxies.
THE Hα/FUV FLUX RATIO AND THE INITIAL MASS FUNCTION

Figure 3 shows strong correlations between the ratio of Hα line flux to FUV continuum flux density, $F_{\text{H}\alpha}/f_{\text{FUV}}$, and (a) $\Sigma_{\text{SFR}}$, and (b) $\Sigma_R$. In panel a (b) the correlation coefficient $r_{xy}$, slope $\alpha$, and dispersion of residuals $\sigma$ are 0.67, 0.47, 0.24 (0.74, 0.59, 0.24) respectively. What drives these strong correlations? The $F_{\text{H}\alpha}/f_{\text{FUV}}$ ratio is very sensitive to the O to B star ratio. The O to B star ratio is in turn affected by the parameters specifying the upper end of the IMF, and the star formation history. Other parameters that affect $F_{\text{H}\alpha}/f_{\text{FUV}}$ are the dust extinction, and the escape fraction $f_{\text{esc}}$ of ionizing radiation. We posit that systematic variation of the IMF parameters are the most likely cause of the correlations seen in Fig. 3.

If there are residual errors in our dust absorption correction then the effect will be to move data along trajectories roughly perpendicular to the observed correlations as shown by the reddening vectors in Fig. 3. The observed correlation can not be created by stretching out uncorrelated data with a spurious extinction correction. Addition of a starburst can cause a short term increase in both $F_{\text{H}\alpha}/f_{\text{FUV}}$ and $\Sigma_{\text{SFR}}$; likewise sharply truncated star formation can cause a decrease in both quantities. However, for star formation history to be behind the observed correlations requires almost as much change in $\Sigma_R$ as $\Sigma_{\text{SFR}}$ which is not possible with plausible population models. The strongest argument against the star formation history scenario is that $F_{\text{H}\alpha}/f_{\text{FUV}}$ also correlates with other global quantities such as $L_R$ (as may be inferred from Fig. 2a) and dynamical mass. Galaxies with low $F_{\text{H}\alpha}/f_{\text{FUV}}$ tend to be low surface brightness dwarf galaxies, while galaxies with high $F_{\text{H}\alpha}/f_{\text{FUV}}$ tend to be high luminosity massive spirals. Such a dramatic range of properties can not be acquired by short term changes in the SFR.
FIGURE 3. The correlations between the Hα to FUV flux ratio $F_{\text{H}\alpha}/f_{\text{FUV}}$ and (a) star formation intensity, as derived from Hα and (b) $R$ band surface brightness. Symbols and line styles are the same as in Fig. 1. The vectors in the bottom right show the effects of dust reddening for two different models. The more vertical of the vectors is the Galactic dust extinction model (Cardelli et al. 1989); the other is the Calzetti (2000) Starburst attenuation law. The length of both vectors in $\log(F_{\text{H}\alpha}/f_{\text{FUV}})$ is set to 0.24 dex which corresponds to an attenuation of the $V$ band stellar continuum of $A_V = 0.33, 0.68$ mag for Galactic and Starburst reddening respectively.

Having $f_{\text{esc}}$ inversely correlated with galaxy mass could cause the observed correlations. $f_{\text{esc}}$ has only been well measured in high surface brightness galaxies. So we can not yet rule out a variable $f_{\text{esc}}$ as the cause of the observed correlations. This would require that dwarf galaxies have an ISM that is more porous to ionizing photons than in more massive galaxies. Dwarf galaxies with porous HI distributions have been observed (e.g. Puche et al. 1992). However dwarf galaxies typically contain a higher fraction of their mass in the ISM (Hanish et al. 2006), while the lower mass densities of their disks suggests that the ISM distribution should be “puffier”. These factors should make it harder for ionizing photons to escape, not easier. Indeed, Oey et al. (2007) argue that $f_{\text{esc}}$ increases with surface brightness.

The observed range in $F_{\text{H}\alpha}/f_{\text{FUV}}$ can be accounted for by plausible adjustments to the parameters affecting the upper end of the IMF. Using Starburst99 population synthesis models (Leitherer et al. 1999, Vázquez & Leitherer 2005) having constant SFR and solar metallicity we find that the range of $F_{\text{H}\alpha}/f_{\text{FUV}}$ can be modeled with an IMF having a Salpeter slope, $\gamma = -2.35$, if the upper mass limit $M_u$ varies between 30 and 120 $M_\odot$, or for a fixed $M_u = 80$ $M_\odot$ if $\gamma$ varies between $-1.1$ and $-3.5$. What is required is that one or both of these properties varies systematically with global galaxy properties.

EXTENDED HI DISKS

In separate work with the Advanced Camera for Survey (ACS) team, we looked for young stars in the extremely extended outer HI disk of NGC 2915 (Meurer et al. 1996)
in two ways. First, we imaged the galaxy in Hα with the Anglo-Australian Telescope and discovered three faint HII regions beyond the Holmberg isophote. Each of these could be ionized by a single late O or early B star. Second, we used ACS on the Hubble Space Telescope to take a deeper look for stellar populations in the outer disk, selecting a field that contained one of the outer HII regions found from the ground. We found a pervasive distribution of old stars including three globular clusters (Meurer et al. 2003) as well as a smattering of blue stars and an open cluster at the position of the HII region. The detection limit of the data corresponds to a mass limit of about 7 $M_\odot$ on the main sequence, hence the blue stars are primarily B stars. The distribution of blue stars is flat in a radial sense, but clumpy and highly correlated with the HI. We found a total of 430 blue stars, which must be predominantly on the main sequence. For a constant SFR population having a Salpeter IMF with $M_u = 100 M_\odot$ one expects an equilibrium B/O star number ratio of 22. The AAT Hα observations allow 1-4 O or late B stars. Hence, the B/O ratio is too high for this IMF by a factor of 5-20. The HI morphology of NGC 2915 is very regular, while the orbital time at the radii probed by the HST observations is $\sim$ 200 Myr, longer than the lifetimes of the stars observed. The high B/O ratio can not be caused by a truncated star formation history - you can’t turn off the galaxy quick enough. The brightest blue stars are at the position of the HII region in the field. There is no evidence for “naked” O stars in the field. Hence the best explanation for the high B/O ratio in this field is a steep $\gamma$ or low $M_u$.

Other examples of O star deficient outer disks have also been reported recently in the literature. A spectacular example is M83 which was used as the primary example of a galaxy with a star formation edge deduced from Hα observations by Martin & Kennicutt (2001). However Thilker et al. (2005) used GALEX observations to demonstrate that the UV emission extends much further than the Hα light with no sign of a star formation-edge in the UV radial profiles.

CONCLUSIONS

Recent work by our teams as well as others has cleared up several open questions. The star formation, HI and stellar light properties of galaxies are tightly correlated as shown by global scaling relations, indicating that an improved form of the star formation law is within reach. This must have the star formation rate dependent on the stellar as well as ISM mass density, perhaps similar to the form suggested by Dopita & Ryder (1994). It makes sense that the stellar mass density should contribute to regulating star formation since in most galaxies stars are the major contributor to the galactic potential of the optically bright portion of galaxies, and hence are key to setting the hydrostatic pressure of galactic disks. It appears that extended HI disks are not empty of stars but have sparse populations of B stars that heat the disk. It is also becoming clear that FUV and Hα properties are different between galaxies and even have different distributions within galaxies. This probably indicates that the B/O ratio varies within and between galaxies, and the most likely explanation for that is the upper end of the IMF is not universal. The only alternative is that the escape fraction of ionizing photons is much larger at the low surface brightness (low mass) end of the star forming galaxy sequence. While this is not ruled out by observations, it is contrary to naive expectations.
Whatever the cause of the systematic $F_{H\alpha}/F_{UV}$ variations there are major implications and many new questions to resolve. What is $f_{esc}$ in low surface brightness galaxies? If the IMF varies, which parameters vary and what drives the variations? What is the best way to measure the SFR of galaxies? Other open questions relate more directly to the $H\text{I}$ - star formation connection. On the most basic level what is the nature of the connection? Is $H\text{I}$ a tracer for the ISM that fuels the star formation, or does it represent the byproduct of the young stellar populations photo-dissociating the molecular ISM they formed out of (e.g. Tilanus & Allen 1993)? Finally, what form of the SFL best explains the inter-relationship between star formation, the existing stars, and the $H\text{I}$ content of galaxies?

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