THE HI MASS–STAR FORMATION RATE RELATION AND SELF-REGULATED STAR FORMATION IN DWARF GALAXIES

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Abstract. We have developed a simple, static model designed to place a very solid lower limit on the star formation rate (SFR) expected in a dwarf disk galaxy, which leads to the prediction of a previously undocumented relation between HI mass, \( M_{\text{HI}} \), and SFR. Over the mass range \( 10^8 \sim 10^{10} M_\odot \), a wide variety of galaxies are observed to follow such a relation — SFR \( \propto M_{\text{HI}}^{4} \) — with the same slope and similar scatter to our prediction. Within the model, this relation is a manifestation of self-regulating star formation (SF), in which the ISM is kept warm and stable by a UV interstellar radiation field (ISRF) that is maintained by constant regeneration of O–B stars. Regardless of the actual mode of star formation, it seems that the majority of dwarfs are presently forming stars in the same way.

1 Introduction

The work presented is derived from an attempt to understand a surprising result from the HI Parkes All-Sky Survey (HPASS): the non-detection of isolated, galactic-scale concentrations of HI with no significant stellar counterpart — baryonic dark galaxies or ‘galaxies without stars’ (Dove et al. 2005). We have presented this study in Taylor & Webster (2005): we find that an HI surface density as low as several \( M_\odot \) pc\(^{-2}\) is sufficient to self-shield against \( \text{H}_2 \) photodissociation by the cosmic background radiation; we argue that within this self-shielded region, a relative \( \text{H}_2 \) abundance of as little as \( 10^{-4} \) is sufficient to initiate a transition to a cold (\( T \lesssim 300 \) K) phase, which greatly increases the chances of gravothermal (Toomre) instability. In short, we conclude that dark galaxies are, at best, exceedingly rare, because there is no mechanism to prevent star formation; wherever possible, self-shielding HI will develop an \( \text{H}_2 \) component that is sufficient to initiate gravothermal instability.

The situation changes once SF is initiated: short-lived O–B stars then provide a second source of photodissociating photons by ignoring internal extinction, and ignored all effects of dust and metals. Since we were interested primarily in ‘galaxies without stars’ (ie. the complete prevention of star formation) we deliberately tailored our assumptions to produce a lower limit on the predicted \( \text{H}_2 \) component that is sufficient to prevent gravothermal instability.

The details of this calculation are presented in Taylor & Webster (2005) and we do not repeat them here. In essence, the argument is this: we solve for the UV (ISRF) energy density required prevent \( \text{H}_2 \) production/cooling and subsequent instabilities; knowing the UV output and lifetime of a massive star, and assuming a standard IMF, it is then possible to determine the SFR required to provide this UV radiation, \( \mathcal{R}_{\text{min}} \). We emphasise that since we were interested primarily in ‘galaxies without stars’ (ie. the complete prevention of star formation) we deliberately tailored our assumptions to produce a lower limit on the predicted \( \text{H}_2 \) abundance and rate of cooling, so making star formation as difficult as possible: in particular, we have allowed ‘maximum damage’ by photodissociating photons by ignoring internal extinction, and ignored all effects of dust and metals.

2 The \( M_{\text{HI}}-\text{SFR} \) Relation

We model the gas distribution using the formalism of Mo, Mao & White (1998), in which each cloud is described by three parameters: the virial mass, \( M_{200} \), the spin parameter \( \lambda \), and the disk mass fraction \( m_d \); in all cases, \( M_{\text{HI}}/m_d M_{200} \) is between 0.56 and 0.70. For each combination of \( \lambda \) and \( m_d \), \( \mathcal{R}_{\text{min}} \propto M_{\text{HI}}^{4} \); our predicted \( M_{\text{HI}}-\text{SFR} \) relation is shown in Figure 1, along with observed values taken from the literature. We note with interest that this relation has the same power as the empirical Schmidt SF law, SFR/\( dA \propto \Sigma_{\text{HI}}^{1.4} \).

The slope of the relation is driven by the distribution of the densest gas in galaxy centres, since it is this gas that requires the most radiation to maintain thermal stability. The scatter is set primarily by the distribution of galactic spins, as well as variations in the relative mass of the disk in comparison to the halo, since, for a fixed mass, these determine the density near the centre. Because the model was designed to place a lower limit on the SFR, it cannot predict the zero-point of such a relation. Within the self-shielded region, the \( \text{H}_2 \) cooling rate is typically less than 1—10 percent of the net cooling rate; a significantly higher ISRF might be required to balance these other cooling mechanisms. Moreover, if there were, for example, a systematic run with mass in the relative contribution of metal-line cooling in comparison to \( \text{H}_2 \) cooling, the inclusion of metals might alter the predicted slope of the relation. We stress that this would only be true, however, if metal-line cooling were important in initiating the transition from warm to cold.
3 Self-Regulated Star Formation in Dwarf Galaxies?

Even though the observational samples were constructed to include widely disparate populations, these populations are not readily distinguished in Figure 1 for $M_{\text{HI}} \gtrsim 10^8 \, M_\odot$, nor are ‘extreme’ objects like DDO 154 and ESO215-G7009 distinguished from ‘normal’ dwarfs in the $M_{\text{HI}}$—SFR plane. In the mass range $M_{\text{HI}} \sim 10^8$—$10^{10} M_\odot$, it seems that essentially all (HI detected) galaxies are presently forming stars in the same way: galaxies follow a tight sequence in the $M_{\text{HI}}$—SFR plane. Moreover, we argue that the general agreement between the character of the predicted and observed $M_{\text{HI}}$—SFR relations lends weight to the physical picture on which our simple model is based: the results in Figure 1 suggest that the well observed population of dwarf galaxies represent the minimum rate of ISRF-regulated SF in galaxies.

References

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Figure 1: Minimum SFR required for stability, $R_{\text{min}}$, plotted against HI mass, $M_{\text{HI}}$. Like models are connected with a dashed line to guide the eye: from top to bottom, models are $(\lambda, m_d) = (0.04, 0.10), (0.04, 0.05), (0.10, 0.10), (0.10, 0.05)$. Note that the top and bottom pairs of lines represent the 50 and 90 percent points of the expected spin distribution, respectively, and that we have deliberately attempted to place a firm lower bound on $R_{\text{min}}$. For comparison, literature values of $M_{\text{HI}}$ and SFR for a variety of dwarf galaxies are overplotted — plusses: 13 Im and Sm dwarfs from Hunter, Elmegreen & Baker (1998); crosses: four HI- bright dwarfs from Young et al. (2003); diamonds: seven LSB and four “normal” dwarfs from van Zee et al. (1997); points: 121 members of a sample of irregular galaxies (points), spanning more than 8 mag in absolute magnitude and surface brightness, from Hunter & Elmegreen (2004); triangles: 10 faint dwarf galaxies from Begum et al. (2005); square: the extremely HI-rich dwarf ESO215-G7009 (large square) (Warren, Jerjen & Koribalski, 2004).