LINKED EVOLUTION OF GAS AND STAR FORMATION IN GALAXIES OVER COSMIC HISTORY

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ABSTRACT

We compare the cosmic evolution of star formation rates in galaxies with that of their neutral hydrogen densities. We highlight the need for neutral hydrogen to be continually replenished from a reservoir of ionized gas to maintain the observed star formation rates in galaxies. Hydrodynamic simulations indicate that the replenishment may occur naturally through gas infall, although measured rates of gas infall in nearby galaxies are insufficient to match consumption. We identify an alternative mechanism for this replenishment, associated with expanding supershells within galaxies. Preexisting ionized gas can cool and recombine efficiently in the walls of supershells, molecular gas can form in situ in shell walls, and shells can compress preexisting molecular clouds to trigger collapse and star formation. We show that this mechanism provides replenishment rates sufficient to maintain both the observed H I mass density and the inferred molecular gas mass density over the redshift range 0 ≤ z ≤ 5.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: ISM — galaxies: starburst — ISM: general — supernovae: general

1. INTRODUCTION

Our understanding of the cosmic star formation history (SFH) of galaxies has progressed significantly over the past decade (e.g., Hopkins 2004; Hopkins & Beacom 2006). In the same time the space density of neutral hydrogen gas has been measured over the majority of cosmic history (see Fig. 8 of Lah et al. 2007). The evolution of the atomic hydrogen (H I) in the universe will be comprehensively determined within the next few years by extremely sensitive surveys with the next generation of radio telescope instrumentation (e.g., van der Hulst et al. 2004; Rawlings et al. 2004; Johnston et al. 2008), and it is timely to consider mechanisms associated with this evolution.

The space density of H I in galaxies appears to evolve surprisingly little from z ≈ 5 to z ≈ 0.2 (Lah et al. 2007), a span of roughly 10 Gyr, the latter half of which sees a decline in the space density of star formation rate (SFR) in galaxies by almost an order of magnitude (e.g., Hopkins & Beacom 2006). Given the SFR density it is easy to show that the H I plus molecular gas at high redshift would be exhausted on timescales of a few Gyr if it were not continually replenished. Erb (2008) presents a model incorporating gas infall, outflows, and consumption by star formation to explain both replenishment and the mass-metallicity relation in high-redshift (z ≈ 2) galaxies.

Hydrodynamic simulations advocating hot and cold modes of accretion indicate that the infall rate closely tracks the star formation rate (e.g., Kereš et al. 2005; Birnboim et al. 2007), with star formation moderated by the rate of infall. The simulations, however, neglect gas outflows from galaxies, which are a significant component of gas depletion. The quantitative infall rates predicted are thus insufficient to maintain a constant H I density in galaxies. Observed rates of gas infall in local galaxies, also, are only about 10% of the star formation rate (Sancisi et al. 2008). The difficulties in explaining replenishment through infall leave the physical mechanism of this replenishment as a critical open question in galaxy evolution.

In this Letter we suggest a mechanism directly associated with the SFR in galaxies that can provide the necessary replenishment of neutral gas to maintain an essentially unevolving, or slowly evolving, H I mass density. We infer the density of gas required to reproduce the observed SFH in § 2. In § 3 we present a number of models for the replenishment of this gas, and show that a replenishment proportional to the SFR density can reproduce the necessary gas mass density. A replenishment mechanism associated with galactic supershells is detailed in § 4, and the results are summarized in § 5. Throughout this analysis we adopt the "737" cosmology with H0 = 70 km s⁻¹ Mpc⁻¹, Ωm = 0.3, ΩΛ = 0.7 (e.g., Spergel et al. 2003).

2. ESTIMATING THE MASS DENSITY OF STAR-FORMING GAS

While our motivation is to understand the observed lack of significant evolution in the H I mass density, we approach this by considering the total mass density of gas available to form stars, which includes molecular as well as atomic gas. We neglect the intricacies in the conversion of H I to molecular gas associated with the star formation process, as this occurs on timescales very short compared to those involved in this analysis. What is important is the total reservoir of gas available for star formation, "star-forming gas," ρ_{SFG}, at a given redshift, comprised of both atomic and molecular gas. Star formation is an inefficient process and ρ_{SFG} will likely be somewhat less than the total of the atomic and molecular gas mass densities.

The cosmic evolution of the H I mass density has been challenging to measure. There is an implicit assumption that the damped Lyα absorbers used to measure the H I mass density at z > 0.3 are representative of the galaxies used to trace the SFH. The best current measurements suggest that this is not an unreasonable assumption (Zwaan & Prochaska 2006), while also highlighting the difficulty in obtaining observational constraints on ρ_{SFG}. In the absence of direct observational measurements, we estimate ρ_{SFG} indirectly from the observed SFH, using the local relationship between gas and SFR surface densities from Kennicutt (1998). We calculate ρ_{SFG} using equation (10) of Hopkins et al. (2005) and the results are shown in Figure 1. The open triangles in Figure 1 are derived from the piecewise linear fit to the SFH of Hopkins & Beacom (2006),

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3 Thanks to Sandhya Rao (Rao et al. 2006) for this terminology.
their Table 2, for their “SalA” initial mass function (IMF). The open squares correspond to the SFH of Wilkins et al. (2008) which assumes an evolving initial mass function. The solid magenta and cyan lines are nominal parameterizations of the possible evolution of the total gas reservoir for each of the SFH cases.

3. THE EVOLUTION OF THE STAR-FORMING GAS

To explore the interaction between gas consumption and replenishment we show the effects of several simple models in Figure 2. All models begin at a look-back time $t_L$ of 12.55 Gyr ($z = 6$) assuming an initial value for their Table 2, for their “SalA” initial mass function (IMF). The open squares correspond to the SFH of Wilkins et al. (2008) which assumes an evolving initial mass function. The solid magenta and cyan lines are nominal parameterizations of the possible evolution of the total gas reservoir for each of the SFH cases.

The SalA IMF is a modified Salpeter IMF with a turnover below 0.5 $M_\odot$ (detailed in Hopkins & Beacom 2006 and Baldry & Glazebrook 2003).

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**Fig. 1.**—The cosmic history of neutral and “star-forming” gas mass density. Filled circles: The H I density as shown in Fig. 8 of Lah et al. (2007). From high to low redshift, the data come from Prochaska et al. (2005) at $z \approx 10$ Gyr ($z > 1.9$); from Rao et al. (2006) in the range $5 \text{ Gyr} < t_r < 9 \text{ Gyr}$ ($0.61 \lesssim z \lesssim 1.22$); the stacking measurement from Lah et al. (2007) at $t_r = 2.8 \text{ Gyr}$ ($z = 0.24$); and the HIPASS measurement of the local H I density from Zwaan et al. (2005). Open red triangles: $\rho_{\text{gas}}$, the neutral plus molecular gas density inferred from the SFH from Hopkins & Beacom (2006) assuming the Kennicutt-Schmidt relation for star formation. Open blue squares: $\rho_{\text{gas}}$ as inferred from the SFH of Wilkins et al. (2008) which assumes an evolving initial mass function. The solid magenta and cyan lines are nominal parameterizations of the possible evolution of the total gas reservoir for each of the SFH cases.

**Fig. 2.**—Models for the evolution in the gas reservoir. The H I mass density (filled circles), $\rho_{\text{gas}}$ (open blue squares), and solid cyan line are as in Figure 1. Dashed line: Predicted gas reservoir evolution assuming no replenishment. Dash-dotted and dash-triple-dotted lines: Two different rates of constant replenishment. Dotted line: Replenishment rate proportional to the SN rate. Heavy solid line: Replenishment rate proportional to the SN rate, but at a factor of 0.95 of that required to balance the consumption. See text for further details.

log $[\rho_{\text{SFG}}/(M_\odot \text{ Mpc}^{-3})] = 8.1$, with $\rho_{\text{SFG}}(t_L)$ calculated simply as the integral over time. At each time step gas is consumed by star formation $[-\dot{\rho}_* (t)]$ and a similar amount in gas outflows. Gas is returned to the interstellar medium (ISM) through stellar evolutionary processes (stellar winds, supernova ejecta) with a recycling fraction of $R$ (e.g., Kennicutt et al. 1994; Madau et al. 1998; Cole et al. 2001), adding a factor $+R\dot{\rho}_*(t)$. For the SalA IMF, $R = 0.4$, while other IMFs will have different recycled fractions (e.g., Hopkins & Beacom 2006). Finally a replenishment factor $K(t)$ is added. This can be expressed as

$$\rho_{\text{SFG}}(t_L) = \rho_{\text{SFG}}(t = 12.55) + \int_{t = 12.55}^{t = t_L} [-1.6\dot{\rho}_*(t) + K(t)] \text{dt}.$$  

(1)

These simplifications hide a wealth of complex ISM and IGM interactions, including the fact that material returned to the ISM through stellar evolution, as well as infalling gas, may contribute to ionized or otherwise non-star-forming components, as well as directly to $\rho_{\text{SFG}}$. These details are subsumed into the effective replenishment factor, $K(t)$.

A model with no gas replenishment, $K(t) = 0$, is shown in Figure 2 (dashed line), emphasizing the rapid consumption timescale. Two models assuming constant rates of replenishment, $K(t) = 0.16 M_\odot \text{ Mpc}^{-3} \text{ Gyr}^{-1}$ (dash-dotted line) and $K(t) = 0.21 M_\odot \text{ Mpc}^{-3} \text{ Gyr}^{-1}$ (dash-triple-dotted line), are also shown. The “bounce” seen in these models arises from an early excess in consumption followed by progressively decreasing consumption as $\rho_*$ declines for $z \approx 1$, predicting excess $\rho_{\text{SFG}}$ at look-back times $t_L < 4–6$ Gyr ($z = 0.4–0.7$).

Replenishment factors proportional to the SFR density provide an obvious way to ensure $\rho_{\text{SFG}}$ remains constant with time.

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4 The SalA IMF is a modified Salpeter IMF with a turnover below 0.5 $M_\odot$ (detailed in Hopkins & Beacom 2006 and Baldry & Glazebrook 2003).
A replenishment factor of \( K(t) = 1.6\rho_* \) in equation (1) gives \( \Delta \rho_{\text{SFR}} = 0 \) at all redshifts (Fig. 2, dotted line). Different constants of proportionality allow for slowly varying changes in \( \rho_{\text{SFR}} \). With \( K(t) = 1.52\rho_* \) (a factor 0.95 of that required for complete replenishment; Erb 2008) the replenishment does not fully balance consumption, and gives a slow decline in the global gas density (Fig. 2, heavy solid line).

In the following section we consider supershells in the ISM as the driver of a physical mechanism for replenishment. Supershells are both directly associated with star formation and are highly efficient at converting hot-phase gas into star-forming gas.

4. DISCUSSION

4.1. A Physical Mechanism for Replenishment

The ISM in galaxies contains expanding supershells or superbubbles associated with previous generations of star formation. We propose that the neutral and molecular gas replenishment in the walls of supershells is sufficient, and of the appropriate form, to provide a natural mechanism explaining the relatively flat evolution in the H i mass density. Supershells are large-scale expanding shells of gas driven by supernovae (SNe) and stellar winds from OB star clusters (Oey 1996; Oey & Smedley 1998; McClure-Griffiths et al. 2001). Supershells have long been suggested to have a triggering effect on subsequent generations of star formation (McCray & Kafatos 1987; Elmegreen 1998; Hartmann et al. 2001; Bergin et al. 2004; Oey et al. 2005), and are effective at replenishing star-forming gas through several mechanisms. First, supershells are efficient at cooling and recombining ionized gas through radiative cooling in shell walls (Koo & McKee 1992). This may be critical in converting gas shock-heated by previous generations of SNe within a galaxy, or new hot-mode infall gas, to a potentially star-forming state, as the 10^6 K gas may otherwise never cool to support subsequent star formation. Second, molecular gas can form from neutral gas in situ in shell walls, where compression and the development of instabilities leads to sufficiently high neutral gas densities to allow for cooling and self-shielding on timescales of 10–20 Myr (Bergin et al. 2004; Hennebelle et al. 2008). Finally, they can compress preexisting molecular material to trigger molecular cloud collapse and star formation (Elmegreen 1998). The timescales for these processes are shorter than or comparable to the supershell lifetime (~20 Myr), which is in turn short compared to the global gas consumption timescale of several Gyr.

To establish whether the replenishment achievable in supershells is sufficient to make this mechanism feasible, we first convert the replenishment rates given in § 3 into a replenished mass per SN event. A replenishment rate proportional to the SFR density is also proportional to the rate of supernova Type II (SNII)*. Converting a proportionality to SFR density into one depending on the SNII rate, \( \rho_{\text{SNII}} \), depends on the assumed IMF. From Hopkins & Beacom (2006) \( \rho_{\text{SNII}} = (0.00915/M_\odot)\rho_* \) for the SalA IMF. The replenishment rate \( K(t) = 1.6\rho_* \) becomes \( K(t) = 174.9\rho_{\text{SNII}} M_\odot \).

The other extreme choice of IMF consistent with the normalization of the SFH (Hopkins & Beacom 2006) is that of Baldry & Glazebrook (2003), hereafter the BG IMF. For the BG IMF \( \rho_{\text{SNII}} = (0.0132/M_\odot)\rho_* \). The recycled fraction is \( R = 0.56 \) (Hopkins & Beacom 2006), changing the consumption term in equation (1) to \(-1.44\rho_*\). The corresponding replenishment rate is \( K(t) = 109.1\rho_{\text{SNII}} M_\odot \). These extremes imply that, depending on the IMF, sufficient gas replenishment to maintain a constant H i mass density with redshift would be achieved if each SN event caused the recombination and cooling of \( \approx 110–180 M_\odot \) of gas. These IMFs are the extrema given the SFH normalization limits, and most reasonable IMFs should result in masses within this range.

Detailed measurements to confirm molecular gas formation within supershells are observationally challenging. We use the limited data currently available to assess the replenishment rates associated with supershells, and to establish whether at least one well-studied supershell achieves the required rate. McClure-Griffiths (2006) and Dawson et al. (2008) have shown explicit cases of molecular clumps along the edges of supershells, suggestive of some degree of in situ formation, with a significant amount of molecular material associated with the supershell walls. The supershell investigated by Dawson et al. (2008) is associated with about \( 2 \times 10^5 M_\odot \) of molecular gas, of which those authors estimate that 80% likely comes from a preexisting giant molecular cloud. Of the remaining \( \approx 10^4 M_\odot \) of molecular gas it is difficult to determine how much is preexisting and how much has been cooled and recombined by the expansion of the shell. We can use \( 4 \times 10^3 M_\odot \) as an upper limit to the replenishment rate. About 30 stars with stellar mass \( M_* > 7 M_\odot \) are required to form this supershell, including stars that may not yet have gone supernova. This gives \( 1300–2000 M_\odot \) of molecular mass replenished per SN event, a limit comfortably encompassing the required rate. This upper limit could change significantly depending on the fraction of preexisting molecular material and also on the fraction of stars that have not yet gone supernova.

Not all SNe lie within supershells, although Higdon & Linnefelter (2005) estimate that a minimum of 65% of SNII should occur in superbubbles, increasing to \( \approx 80\%–90\% \) when the spatial and temporal correlations of stellar clusters are considered. If 80% of SNII are associated with supershells, for example, this would increase the required replenishment rate per SN to \( \approx 140–230 M_\odot \). But even if as few as 10% of all SNII contribute in this way to the replenishment, the rate implied by the results of Dawson et al. (2008) would still be sufficient. This confirms that the necessary replenishment rates are likely to be achievable within supershells.

The observed decline by a factor of 2 in the H i mass density may be a natural consequence of a replenishment rate about 95% of that required to match consumption, as shown by the heavy solid line in Figure 2. If the actual replenishment rate from supershells lies somewhere between the required rate and our derived upper limit, however, there may in fact be too much newly replenished gas to allow any decline in the neutral gas mass density. A possible resolution in this scenario would be increasing the proportionality between the gas outflow rates and the SFR as redshift decreases. This is not unreasonable, as the SFH is becoming progressively more dominated by lower mass galaxies with decreasing redshift (Juneau et al. 2005; Panter et al. 2007; Mobasher et al. 2008). Galaxies with stellar masses \( M_* \approx 10^{10} M_\odot \) dominate the SFH at \( z \approx 1 \) (Mobasher et al. 2008). Such low-mass galaxies lose more mass in gas outflows in proportion to their SFR than high-mass galaxies, simply due to the former’s shallower potential wells (e.g., Dekel & Silk 1986; Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000). This effect may contribute to the slow decline in the H i mass density.

4.2. Limitations of the Proposed Mechanism

We have treated a number of complex physical processes in very general terms. While being cautious of oversimplification,
we have attempted to capture the essential interactions between star formation, recycling from stellar evolutionary processes, ISM processes of heating and ionization, recombination, cooling, and molecule formation, together with infall from the IGM and outflow of ISM material. Most of this complexity is concealed within the replenishment factor $K(t)$.

One issue is that stellar winds and SNe contribute to all components of the ISM rather than solely to $\rho_{\text{gas}}$. In a "galactic fountain" (Shapiro & Field 1976; Houck & Bregman 1990), infalling gas will contribute to, and outflowing gas will strip from, all components. If recycled gas includes a component that never subsequently forms stars (such as some recycled gas in the ionized phase being ejected from the galaxy before contributing to star formation), the factor $+\dot{R}_{\text{in}}(t)$ in equation (1) will be reduced and $K(t)$ will need to be increased to compensate.

Our quantitative results strongly depend on the assumed gas outflow rate. Variations by a factor of 2 or so in either direction will still result in a constant or slowly varying H i mass density, as long as a proportionality with the SFR of the host galaxies remains (as suggested by Veilleux et al. 2005). The chosen outflow rate is an effective average over all star-forming galaxies and is consistent with observed trends (e.g., Martin 1999; Pettini et al. 2000; Veilleux et al. 2005). While individual galaxies show a large observed scatter between outflow rates and SFRs, for the ensemble properties of the total population this assumption should be robust.

The proposed replenishment through the supershell mechanism is not inconsistent with some simultaneous replenishment through infall. Metallicity considerations, which we do not address here, do require infall of some low-metallicity gas (Erb 2008), and gas infall in local galaxies is well established (e.g., Bland-Hawthorn et al. 2007; Sancisi et al. 2008), although the observed infall rate is insufficient to match consumption.

5. SUMMARY

We have identified a possible resolution to the puzzle of why the H i mass density of the universe evolves so little for so much of cosmic history. We propose that replenishment is driven by supershells associated with star-forming complexes in galaxies. Preexisting ionized gas efficiently cools and recombines in supershell walls. Molecular gas forms in situ in shell walls, and molecular material is compressed to trigger cloud collapse and star formation. This mechanism provides a natural explanation for replenishment that has the desired proportionality to the SN rate. The level of replenishment observed in a Galactic supershell (Dawson et al. 2008) appears more than sufficient to provide the required replenishment rate of $\approx 110-180 \, M_\odot$ per SN event.

The factor of 2 decline in the H i density between $z \approx 0.2$ and $z = 0$ could be explained through either (1) a replenishment rate that is marginally lower than that required to exactly balance gas consumption; or (2) the inability of low-mass galaxies, which dominate the star formation history in this epoch, to retain their newly formed H i; or, perhaps more likely, a combination of both.

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