DEVIANOS FROM THE SCHMIDT–KENNICUTT RELATIONS DURING EARLY GALAXY EVOLUTION

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ABSTRACT

We utilize detailed time-varying models of the coupled evolution of stars and the H1, H2, and CO-bright H2 gas phases in galaxy-sized numerical simulations to explore the evolution of gas-rich and/or metal-poor systems, which are expected to be numerous in the early universe. The inclusion of the CO-bright H2 gas phase and the realistic rendering of star formation as an H2-regulated process (and the new feedback processes that this entails) allow the most realistic tracking of strongly evolving galaxies and much better comparison with observations. We find that while galaxies eventually settle into states conforming to the Schmidt–Kennicutt (S-K) relations, significant and systematic deviations of their star formation rates (SFRs) from the latter occur, and are especially pronounced and prolonged for metal-poor systems. The largest such deviations occur for gas-rich galaxies during not only the early evolutionary stages but also during brief periods at later stages. Given that gas-rich and/or metal-poor states of present-epoch galaxies are expected in the early universe while a much larger number of mergers frequently reset non-isolated systems to gas-rich states, even brief periods of sustained deviations of their SFRs from those expected from the S-K relations may come to characterize significant periods of their stellar mass built-up. This indicates potentially serious limitations of S-K-type relations as reliable sub-grid elements of star formation physics in simulations of structure formation in the early universe. We anticipate that galaxies with marked deviations from the S-K relations will be found at high redshifts as unbiased inventories of total gas mass become possible with ALMA and the EVLA.

Key words: galaxies: evolution – galaxies: formation – galaxies: star formation – ISM: atoms – ISM: molecules – methods: numerical

1. INTRODUCTION

Since it was first proposed as a phenomenological relation linking H1 gas mass and star formation surface density in galaxies (Schmidt 1959), and subsequently better constrained and re-formulated as to also include CO-bright H2 gas (Kennicutt 1998, 2008), the Schmidt–Kennicutt (hereafter S-K) relation, \( \Sigma_{\text{SFR}} \propto [\Sigma(H_1)]^k \) \((k \sim 1–2)\), has provided the standard observational framework relating the star formation rate (SFR; as a surface density rate \( \Sigma_{\text{SFR}} \)) to the gas supply in galaxies. It is also an important element of the sub-grid star formation physics incorporated into galaxy evolution and structure formation models (e.g., Baugh 2005 and references therein; Springel et al. 2005; Schaye & Della Vecchia 2008), where numerical resolution limitations preclude a more detailed treatment of star formation over the scales involved. Many theoretical (Dopita & Ryder 1994; Robertson & Kravtsov 2008) and observational (e.g., Wong & Blitz 2002; Bigiel et al. 2008) studies have been made to demonstrate its validity, with the most important recent advances being the identification of the CO-bright H2 gas as better correlated to star formation in galaxies than atomic hydrogen (Wong & Blitz 2002), and the direct star formation role of its dense phase \( (n(H_2) > 10^3 \text{ cm}^{-3}) \) with \( k \sim 1 \) (Gao & Solomon 2004).

Unfortunately, past analytical and numerical investigations of the S-K relation did not include a multi-phase interstellar medium (ISM; though see Gerritsen 1997 for an early investigation that includes this, as well as Robertson & Kravtsov 2008 for recent such multi-phase ISM models) or assumed sub-grid models reacting instantaneously to changes in the global state of the ISM. Thus, they are ill suited to explore very gas-rich systems and/or early galaxy evolutionary stages, when the various ISM phases and their interplay with the stellar content have not yet established equilibrium. Finally, such models cannot be compared directly to observations since they do not include the H2 gas phase (the direct fuel of star formation) or do not model the CO molecule, and thus their direct comparison to observations is problematic (e.g., Gnedin et al. 2009). The latter is the case especially in a metal-poor and/or far-UV intense ISM environment (e.g., Israel 1997; Maloney & Black 1988; Pak et al. 1998), which is common during the gas-rich and vigorously star-forming epochs in early galaxy evolution.

1.1. ISM+Stars Galaxy Models: Features and Limitations

Here, we use our time-varying models of the coupled evolution of H1, H2 gas phases and stars in galaxy-sized numerical simulations to investigate the emergence and possible deviations from the S-K relations. Full details and tests of our method can be found in Pelupessy et al. (2006) and Pelupessy & Papadopoulos (2009). We use an N-body/smoothed particle hydrodynamics code and solve for the full thermodynamic evolution of the Warm Neutral Medium (WNM) and Cold Neutral Medium (CNM) H1 phases (see Wolfire et al. 2003) assuming neither an equilibrium nor an effective equation of state, unlike most current cosmological or galaxy-sized structure formation models (e.g., Springel & Hernquist 2003; Cox et al. 2006a, 2006b; Narayanan et al. 2009). It is worth pointing out that in such models the coldest ISM phase tracked is usually at \( T \approx 10^4 \text{ K} \), which is common during the gas-rich and vigorously star-forming epochs in early galaxy evolution.
via a Jeans mass criterion, the thermal state of the gas is tracked explicitly, while an \( H_2 \)-richness criterion for star formation can be applied in addition to that of gravitational instability (see Pelupessy & Papadopoulos 2009 for details).

The code tracks the \( H_2 \) phase with a physical model for substructure using a minimal set of assumptions. It follows \( H_2 \) formation on dust grains and its thermal and far-UV induced destruction, accounting for self-shielding and dust shielding. The CO-bright \( H_2 \) phase is identified as a post-processing step, destruction, accounting for self-shielding and dust shielding. Formation on dust grains and its thermal and far-UV induced destruction, accounting for self-shielding and dust shielding.

\[ \text{formation regulator in the dynamical setting of an evolving galaxy models} \]

\[ \text{use the most important chemical reactions} \]

\[ \text{(Röllig et al. 2006)} \]

\[ \text{dwarf gas mass fraction as a star formation criterion} \]

\[ \text{S-K(H}_{2}\text{)} \]

\[ \text{significant deviations from the S-K relations, especially the CO-derived gas and star distributions are extracted and mapped.} \]

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\[ \text{The models are run for} \approx \text{1 Gyr, after which the resulting gas and star distributions are extracted and mapped.} \]

\[ \text{2.1. Model Runs and Results} \]

The galaxy models we use utilize the semi-analytic disc galaxy models of Mo et al. (1998) and Springel et al. (2005), which consist of a standard exponential stellar and a gaseous component embedded in a dark halo with a Hernquist profile (Table 1 gives an overview of their properties). The \( H_2 \) gas mass and its CO-bright fractions are very sensitive to the metallicity \( Z \) (Pelupessy & Papadopoulos 2009), and we thus examine models at \( Z = Z_\odot \) and \( Z = Z_\odot/5 \). Finally, we explore systems with gas mass fractions ranging from those typical in present-epoch galaxies (10%–20%) to those found recently in spiral disks at high redshifts (50%) and even up to almost completely gaseous systems (99%) representing the earliest stages in galaxy evolution. The runs start from gravitational and hydrodynamical equilibrium (which is not a thermodynamic, chemical, or SF equilibrium) and with all the gas initially at a WNM H1 phase. Such initial conditions can be seen as rough proxies for the states expected as results of (minor) mergers or infall from cold flows. An initial WNM phase for the H1 gas reservoir is deemed suitable for diffuse, far-UV-illuminated gas of the type observed at high Galactic latitudes and expected at large galactocentric distances of spiral galaxies (e.g., Maloney 1993; Kaufmann et al. 2009). The models are run for \approx 1 Gyr, after which the resulting gas and star distributions are extracted and mapped.

\[ \text{2. EMERGENT S-K RELATIONS AND DEVIATIONS} \]

Stationary galaxy models show that S-K relations appear to hold for variety of galaxy types and ISM conditions (e.g., Dopita & Ryder 1994; Robertson & Kravtsov 2008), while early dynamic modeling (albeit without \( H_2 \) included, and utilizing a much simplified ISM picture) shows such relations emerging after a dynamic equilibrium between ISM phases (WNM and CNM H1) and star formation has been established (Gerritsen & Icke 1997).

\[ \text{Table 1: Overview of Galaxy Model Parameters} \]

| Model | \( M_{\text{dwarf}} (M_\odot) \) | \( M_{\text{halo}} (M_\odot) \) | \( f_{\text{gas}} \) | \( m_{\text{par}} (M_\odot) \) | \( Z \) | \( R_{\text{gas}} \) (kpc) | \( \Sigma_{\text{gas}} \) (M_\odot pc\(^{-2}\)) | \( R_{\text{disk}} \) (kpc) | \( \Sigma_{\text{disk}} \) (M_\odot pc\(^{-2}\)) |
|-------|-----------------|-----------------|--------|-----------------|-----|-----------------|-----------------|-----------------|-----------------|
| A1    | \( 10^8 \)      | \( 2.3 \times 10^9 \) | 0.5    | 200             | 0.2 | 1.5             | 30              | 0.2             | 200             |
| B1    | \( 10^9 \)      | \( 2.3 \times 10^9 \) | 0.2    | 500             | 0.2 | 4.2             | 16              | 0.5             | 450             |
| C1    | \( 10^9 \)      | \( 2.3 \times 10^9 \) | 0.2    | 500             | 1.0 | 4.2             | 16              | 0.5             | 450             |
| D1    | \( 10^9 \)      | \( 2.3 \times 10^9 \) | 0.99   | 1000            | 1.0 | 4.5             | 280             | 0.5             | 5               |
| E1    | \( 10^9 \)      | \( 2.3 \times 10^9 \) | 0.99   | 1000            | 0.2 | 4.5             | 280             | 0.5             | 5               |
| F1    | \( 10^{10} \)   | \( 2.3 \times 10^{10} \) | 0.1    | 500             | 1.0 | 12              | 40              | 1.4             | 670             |
| G1    | \( 10^{10} \)   | \( 2.3 \times 10^{10} \) | 0.5    | 2500            | 0.2 | 12              | 200             | 1.4             | 370             |
| H1    | \( 10^{10} \)   | \( 2.3 \times 10^{10} \) | 0.5    | 2500            | 1.0 | 12              | 200             | 1.4             | 370             |

Notes. The models are labeled with letters A–H with their structural parameters (e.g., mass, metallicity) listed. The effects of different resolutions are discussed elsewhere (Pelupessy & Papadopoulos 2009). The gas distributions of models D1 and E1 consist of equal mass exponential and extended disks; the others have purely extended gas distributions. \( R_{\text{gas}} \) gives the extent of the gas disk, \( \Sigma_{\text{gas}} \), the central gas surface density, \( R_{\text{disk}} \) the exponential scale length of the stellar disk, and \( \Sigma_{\text{disk}} \) the stellar density in the center.
regions very fast, which in turn destroy the CO. The fact that this behavior emerges for both a small (A1) and a 10× larger metal-poor system (B1) suggests that this SFR “oscillation” with respect to an S-K(CO) relation (Figure 1) is not due to mere stochastic scatter from a smaller number of star-forming sites.

Significant and systematic deviations from the S-K(H1+H2) relation during early galaxy evolution epochs (T ≲ 0.2–0.3 Gyr) occur for most of our models and are particularly pronounced for very gas-rich systems (Figure 1: E1, D1 models). The latter relation, a common sub-grid element of cosmological structure formation models, thus seems inapplicable during periods of strong galaxy evolution. Unfortunately, the S-K(H2) relation may not fare much better during such epochs (e.g., C1, E1 in Figure 1, and F1 in Figure 2), and only S-K(CO) remains a good predictor of the underlying star formation at early evolutionary times. The latter occurs for metal-rich systems with moderate amounts of gas (e.g., C1, C1-MR in Figure 1, and F1, F1-MR in Figure 2), i.e., systems like those used to derive the S-K relation in the local universe. The S-K(CO) relation fares better since CO forms only in the dense and cold regions of the H2 gas phase and thus tracks the SF sites more closely, but even this observable relation seems to underpredict the true SFR in very gas-rich systems (Figure 1: D1, E1). This happens even for the metal-rich system (D1) where CO tracks the H2 distribution well, and thus these deviations are not due to CO failing to trace the H2 gas. During those early epochs, gas-rich systems can appear as undergoing periods of very efficient star formation (i.e., little CO-bright H2 gas but strong ongoing star formation), and application of the S-K(CO) relation using their observed SFRs would thus imply much more molecular gas than actually present.

Epochs during which the actual SFRs can be significantly lower than the S-K-predicted ones also exist (e.g., in A1, A1-MR, B1, E1, E1-MR) and are indeed expected during intervals of strong galaxy evolution when large, out-of-equilibrium, amounts of warm (∼103–104 K) H1 and H2 gas mass are produced by spatially extended and almost coherent starburst episodes. During such times, the star-forming CNM H2 gas phase may contain little mass yet the S-K(H1+H2) relation cannot account for this as it considers all the gas as star formation “fuel,” even when in a phase thermodynamically far removed from the one actually forming stars in galaxies. In metal-poor systems, rather surprisingly, we also find periods where even
CO-bright gas experiences star formation lower than expected from the S-K(CO) relation, and this can happen even during later evolutionary times (models: A1, B1, E1). A recent study of low-metallicity high-redshift systems using cosmological-sized simulations also finds marked deviations of the actual SFR from that expected from the S-K relations (Gnedin & Kravtsov 2010) although its applicability to actual observations is hindered by the fact that the CO molecule (the true observable) is not considered. Moreover, the larger volumes modeled in such studies necessitate the use of more sub-grid physics of, e.g., H$_2$ formation, which in turn can make their galaxy-sized results more dependent on the particular assumptions made to set up the sub-grid ISM model.

Examining the earliest epochs ($T < 150$ Myr) of our most massive galaxy models at a finer time step yields better resolved deviations of their intrinsic SFRs from those predicted by the S-K relations (Figures 2 and 3). During those early times, when the evolution of a galaxy is strongest, these deviations are the largest and remain most prominent in very gas-rich systems (e.g., D1, E1 in Figure 2), while they persist for longer times in the metal-poor ones (E1 in Figure 1). However, it must be pointed out that significant deviations can still be found in galaxies with lower gas fractions, typical in the local universe (e.g., models A1, A1-MR, B1, B1-MR in Figure 1). These are within the significant dispersion of actual SFRs around the S-K relation observed in systems in the local universe ($\sim$ a factor of 10) and suggest limitations of such relations as reliable predictive tools of SFR for a given amount of gas to better than an order of magnitude, even for normal galaxies. If, as our simulations suggest, such a dispersion is mostly non-stochastic in nature and the result of the various feedback factors in action (e.g., SNR-induced shocks, far-UV radiation variations, strong non-equilibrium WNM$\leftrightarrow$CNM H$_1$ mass exchange), then use of S-K relations as sub-grid elements of star formation physics in galaxy formation models can impart serious limitations on their predictive power even for present-epoch disk galaxies.

2.2. Evolution of the Largest Gas-rich Systems

Interestingly, the largest disk with the smallest gas mass fraction and a solar metallicity (model F1) settles relatively quickly into full conformance with the S-K relations after $\sim$50 Myr (Figure 2), and this is the type of system for which such relations have been established in the local universe. Moreover, unlike previous cases, the SFR deduced from the S-K(CO) relation now remains close to the actual one (Figure 2, models: F1, F1-MR), even during those first 50 Myr of strong SFR time dependence and its large deviations from the S-K (H$_1$+H$_2$) and S-K(H$_2$) relations. This underscores the central role of the CO-bright H$_2$ gas as the phase most closely associated with the star-forming sites, reflecting the fact that CO forms in the densest regions of the CNM H$_2$ gas, which are also the regions where star formation happens and proceeds fastest.

For disks with the same size but gas mass fractions of 50%, akin to galaxies found recently at high redshifts (Daddi et al. 2010; Tacconi et al. 2010), we find the largest and most sustained deviations of the actual SFR from the S-K(H$_1$+H$_2$) relation (Figure 3). The S-K(H$_2$) and even more so the S-K(CO) relation follow SFR($t$) more closely though significant deviations still exist. Thus, structure formation models where star formation of such disks is followed using an S-K(H$_1$+H$_2$) relation as a sub-grid element of star formation physics may significantly underestimate the rate of stellar mass built-up.

3. DISCUSSION

In the local universe, large variations of the so-called star formation efficiency $SFE = SFR/M_{gas}$ have been found in galaxies, with the very H$_2$-rich ultraluminous infrared galaxies...
(ULIRGs) having 10× or higher SFEs than quiescent spirals. If the framework of the S-K relation is maintained, such variations imply different (k) exponents for different galaxy types, with ULIRGs having k ~ 1, while quiescent spirals and H I-rich objects reaching up to k ~ 2 (Schmidt 1959; Wong & Blitz 2002; Gao & Solomon 2004). This has been attributed to a strongly varying fraction of the SF-fueling versus the total gas reservoir among galaxies, with the CO-bright molecular gas and its even denser HCN-bright phase as the actual star-forming gas (Wong & Blitz 2002; Gao & Solomon 2004; Wu et al. 2005). Our numerical simulations corroborate this picture and further reveal S-K deviations as the complex outcome of strong, non-linear, and highly non-equilibrium mass and energy exchange among the various ISM phases and the stellar component during times of strong galaxy evolution. In that regard, the varying global SFEs and k-values then simply reflect the ergodic “unfolding” of such non-equilibrium events over sets of galaxies in the local universe and the attempts to parameterize it in a simple fashion (i.e., in terms of S-K relations). The significant dispersion that is typically observed around the S-K relation (factors of ~5–10 when derived for systems spanning a large range of properties and SFRs) is then simply masking a deeper set of ongoing physical processes in the ISM of star-forming galaxies. As our simulations suggest, during strong galaxy evolution such processes can set star formation wandering significantly above or below a “mean” S-K relation, much reducing its predictive power.

3.1. Current Observational Evidence and Biases

Unfortunately, unbiased studies of the relation between star formation and the ambient gas supply are currently possible only in the local universe, with an unbiased census of the total gas mass being the main obstacle at high redshifts. This is because currently neither H I nor the CO-bright H 2 gas mass distribution can be routinely imaged (via the 21 cm and CO J=1–0 lines) in high redshift galaxies. Thus, a high-z study of the S-K relation using exactly the same gas mass tracers used to establish it locally is not possible at present. Our simulations indicate that gas-rich systems can stay close to the S-K(CO) relation but deviate substantially from the S-K(HI+H 2) one. Moreover, since currently only CO J=1–0, J+1≥3 line observations are typically available for the distant universe, they introduce a bias toward the dense and warm star-forming molecular gas, which in turn can lead to a seemingly constant S-K(CO high-J) relation across the cosmic epoch (e.g., Tacconi et al. 2010). This may simply reflect the fact that the dense molecular gas excising such high-J CO lines remains the direct “fuel” of star formation with an almost constant SF efficiency in all galaxies (e.g., Gao & Solomon 2004) across the cosmic epoch but leaves open questions regarding the S-K(H I+H 2) or even the S-K(CO) relation (established with the CO J=1–0 line) in gas-rich systems at high redshifts.

There are some early indications for high-redshift systems with much higher SFRs for the amount of CO-bright H 2 gas they contain (e.g., UV optically selected galaxies, Tacconi et al. 2008; or radio-selected starburst galaxies at z ∼ 2, Chapman et al. 2008) as well as evidence for systems with large CO-bright molecular gas reservoirs but with ≳10 times lower SFRs than those expected from the S-K(CO) relation (Nesvadba et al. 2009; Elbaz et al. 2009; Dannerbauer et al. 2009). From our study, we expect that once much less biased gas mass measurements in the distant universe become possible with ALMA and the EVLA, galaxies systematically deviating from S-K-type phenomenological relations will be uncovered and such deviations will be especially prominent for metal-poor and/or very gas-rich star-forming systems.

4. CONCLUSIONS

Our results are of special importance for the modeling of very gas-rich and/or metal-poor progenitors of present-epoch galaxies found in the distant universe, or systems where major gas accretion events frequently “reset” their evolutionary states back to gas-rich ones. In such cases, the non-equilibrium, non-linear, mass/energy exchange between the various ISM phases and the stellar component may come to dominate significant periods of intense star formation and stellar mass built-up during which the S-K relation is not applicable. In short, we find that it may work well for present-epoch metal-rich spirals with modest remaining gas mass fractions (i.e., systems for which the S-K relations were originally deduced) but not for their very gas-rich/metal-poor progenitors in the early universe. The importance of such deviations of the actual SFRs from those expected from the S-K relations does not lie so much in their magnitude (though this must be explored further for gas-rich systems larger than the ones modeled here) as in their systematic nature (e.g., star-forming systems spending certain periods with always higher or always lower SFRs than those estimated from the S-K relations). It is the latter that may make such phenomenological relations poor choices for the sub-grid
physics of star formation in rigorous structure formation models in a cosmological setting.

Finally, we note that when it comes to the large gas-rich galaxies that are currently accessible at high redshifts, our results, drawn for less massive systems, remain provisional. Nevertheless, for more massive and very gas-rich star-forming systems, the larger amplitudes of ISM equilibrium-perturbing agents (e.g., SNs, far-UV radiation fields) and the shorter timescales characterizing their variations will more likely than not exaggerate the deviations of true star formation versus the one expected from S-K-type phenomenological relations. An unbiased observational effort to find and study S-K-deviant galaxies at high redshifts (soon to be possible with ALMA and the EVLA over a wide range of galaxy masses), as well as extending detailed numerical modeling of gas and stars toward larger systems (as computational capabilities improve), is important in establishing the validity range of S-K relations and thus their utility as an important sub-grid element in models of structure formation in the universe.

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