THE MILKY WAY AS A HIGH-REDSHIFT GALAXY: THE IMPORTANCE OF THICK DISK FORMATION IN GALAXIES

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ABSTRACT

We compare the star formation history and dynamics of the Milky Way (MW) with the properties of distant disk galaxies. During the first $\sim 4$ Gyr of its evolution, the MW formed stars with a high star formation intensity (SFI), $\Sigma_{\text{SFR}} \approx 0.6 M_\odot$ yr$^{-1}$ kpc$^{-2}$ and as a result, generated outflows and high turbulence in its interstellar medium (ISM). This intense phase of star formation corresponds to the formation of the thick disk. The formation of the thick disk is a crucial phase that enables the MW to have formed approximately half of its total stellar mass by $z \sim 1$ which is similar to “MW progenitor galaxies” selected by abundance matching. This agreement suggests that the formation of the thick disk may be a generic evolutionary phase in disk galaxies. Using a simple energy injection–kinetic energy relationship between the one-dimensional velocity dispersion and SFI, we can reproduce the average perpendicular dispersion in stellar velocities of the MW with age. This relationship, its inferred evolution, and required efficiency are consistent with observations of galaxies from $z \approx 0$–3. The high turbulence generated by intense star formation naturally resulted in a thick disk, a chemically well-mixed ISM, and is the mechanism that links the evolution of MW to the observed characteristics of distant disk galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: ISM – galaxies: kinematics and dynamics – Galaxy: evolution

Online-only material: color figures

1. INTRODUCTION

The physical processes that regulate the growth and evolution of galaxies are both complex and myriad (e.g., Hopkins et al. 2013). There will likely be no single methodology that enables us to unravel the physics underpinning the variety of phenomena we observe in galaxies as a function of epoch and galactic environment. However, one avenue which may allow us to obtain a deeper understanding of these processes is to use the findings of in situ galaxy studies—observing how the ensemble of galaxies changes with look-back time—and galactic archeology—the unraveling of the detailed star formation, dynamical, and chemical and elemental history through observation of individual stars or simple stellar populations (e.g., globular clusters) in nearby galaxies. Such analyses, as our knowledge from the direct study of galaxies over a wide range of redshifts and galactic archeology grows, become more robust.

That is the purpose and novelty of this Letter; we use the star formation history (SFH) and dynamical evolution of stars in the Milky Way (MW; Haywood et al. 2013; Snaith et al. 2014) to connect quantitatively its cosmic evolution to the observed dynamical evolution and the physical characteristics of high-redshift disk galaxies. Specifically, we will compare the stellar mass growth and star formation rates (SFRs), star formation intensity (SFI), and the stellar and gas kinematics of MW, to the dynamical and star formation properties of distant disk galaxies. In Haywood et al. (2013), we proposed that the formation of the thick disk represented an important phase of the evolution of the MW both in its stellar mass growth and its influence over subsequent evolution of the MW. But can we physically link this phase to what is known about distant galaxies?

Star-forming galaxies at high redshift accumulate their stellar masses in a systematic way as seen in the evolving ridge lines in the SFR–stellar mass plane (SFR–$M_\star$, e.g., Daddi et al. 2007; Elbaz et al. 2007; Reddy et al. 2012), Snaith et al. (2014) showed that the MW has a similar SFH as that of possible MW-like progenitor galaxies selected by abundance matching (van Dokkum et al. 2013) or by their evolution in the SFR–$M_\star$ plane (Patel et al. 2013). Does the MW accumulate its stellar mass in the same way as distant galaxies do in the SFR–$M_\star$ plane?

Comparisons between the evolution of MW progenitors and the dynamical evolution and growth of the MW, as inferred from the dynamics and elemental abundances of stars in the solar vicinity, allows us to link the properties of the MW to the physical conditions of the interstellar medium (ISM) in distant galaxies. Disk galaxies at high redshift are known to be highly turbulent (e.g., Lehnert et al. 2009). Broad spatially resolved line emission from the warm ionized and cold molecular gas are observed in distant galaxies (e.g., Lehnert et al. 2009; Swinbank et al. 2011; Menéndez-Delmestre et al. 2013). Lehnert et al. (2009, 2013) suggested that the broad lines observed are a result of turbulence and bulk motions generated by the mechanical and radiative energy output from the intense star formation occurring within these galaxies. If the MW formed a significant fraction of its stellar mass at $1 < z < 4$ via similarly intense star formation, then there must be a fossil record of this vigorous energy injection in the kinematics and elemental abundances of its individual stars. By quantifying the relationships between the stellar and gas dynamics and SFI at different epochs for the MW, we suggest that this fossil record is in the thick disk, and that indeed thick disks must be a generic evolutionary phase of disk galaxy formation, representing the imprint of the intense star formation observed in disk galaxies at high redshift.

2. THE MILKY WAY AS AN EVOLVING STAR-FORMING GALAXY

To investigate how the MW evolved compared to galaxies observed at various epochs, we use the SFH and velocity
dispersions of stars from Haywood et al. (2013) and Snaith et al. (2014), specific points in the MW's growth history of the MW are similar to that of abundance-matched galaxies, mean that the two SFHs are comparable (Figure 2 in Snaith et al. 2014). Specifically, the uncertainties in the ages of the oldest stars of the MW are ~1 Gyr (10% uncertainty) result in large differences in the corresponding redshifts (the difference in look-back time between redshifts 2 and 4 is ~1 Gyr).

Even allowing for such shifts in redshift, two things are clear: the position of the MW in the SFR–stellar mass plane lies below the ridge lines over z = 0–3 and the stellar mass growth rate at early times is more rapid than predicted by gas accretion models (e.g., Naab & Ostriker 2006; Pipino et al. 2013, Figure 1). These models significantly underestimate the impact of the formation of the thick disk and the total stellar mass formed during this epoch.

2.2. Star Formation Intensity Evolution

During its formation, the thick disk had a short radial scale length (Bovy et al. 2012) and a high SFR and thus likely a high SFI. If the star formation is sufficiently intense, the young MW may have generated outflows (Lehnert & Heckman 1996). Outflows from galaxies play a crucial role in establishing relationships among galaxies such as the mass–metallicity relationship, the metallicity–radius relation, and many others (Heckman et al. 2000). To understand the role of the energy output of massive stars in determining the properties of the MW, we estimate the evolution of its SFI (ΣSFR = SFR/2πr_d^2; Figure 2). Currently, there is no known way to connect the change in the radial scale length of the MW's disk to stellar ages and thus its size evolution. The simplest model consistent with the data is one where the thick disk has a scale length, r_d = 1.8 kpc, and the thin disk has a radial scale length, r_d = 3.6 kpc (Bensby et al. 2011; Bovy et al. 2012). The transition between the thick and thin disk occurs at the end of the thick disk phase (~9 Gyr ago, Figure 2; Haywood et al. 2013). Before discussing the implications of the MW’s resulting SFI, we emphasize that changing the functional form for the temporal evolution of the MW’s scale length does not change SFI (z) significantly. Selecting an evolution with a smooth transition from thick to thin disk, for example, a three-segment evolution of the scale length, shows that adopting different time-dependent r_d(z) do not significantly change the overall evolution of ΣSFR (Figure 2)—the break in the SFI intensity was predominately due to the dip in the SFR.

Irrespective of the precise form of the radial-scale evolution of the MW disk, the MW was likely driving outflows and generating significant levels of turbulence during the formation of its thick disk. The SFI of the MW during it thick disk formation phase lies above that required to generate strong outflows in the local universe (Figure 2; e.g., Lehnert & Heckman 1996). This finding is fundamental to understanding the early evolution of the MW: the structure and kinematics of the thick disk, characterized by large scale heights and high velocity dispersion of its stellar population (Bovy et al. 2012;
Haywood et al. (2013), is likely a direct result of the intense star formation generating a highly turbulent ISM. Importantly for the chemical evolution of the MW and the lack of radial metallicity gradients found in the MW (Cheng et al. 2012), high levels of turbulence will naturally lead to a vigorous mixing and weakening, perhaps destroying, any intrinsic gradients in the disk. A vertical metallicity gradient may develop if the thick disk had progressively lower scale height and became more metal-rich as it grew (Haywood et al. 2013). A decreasing scale height is expected due to the increasing stellar surface and mass density of the disk. Subsequently, the MW evolved rather quiescently, its SFI was low, which would naturally lead to lower dispersions in the gas and stars forming a thin disk (e.g., Dib et al. 2006; Lehnert et al. 2013). These results suggest a direct link between the conditions of the ISM in the evolving MW and the formation of its thick and thin disks.

Interestingly, the MW disk beyond 10 kpc has properties different from those of the inner thin disk, in particular a break in metallicity (a situation observed in other galaxies; Bresolin et al. 2012), but has similar [$\alpha$/Fe] as the young thick disk (Haywood et al. 2013). Although the inner and outer disks seem otherwise rather discontinuous, outflows are a plausible explanation for the similar abundance patterns suggesting that not all the outflowing material escaped.

2.3. Velocity Dispersion Evolution of the Stars and Gas: Relation to the SFI

Lehnert et al. (2009, 2013) proposed that the spatially resolved broad (50–250 km s$^{-1}$) optical emission line gas observed in distant (z $\approx$ 2) galaxies are due to high levels of turbulence and bulk flows generated by the energy output of young stars. Furthermore, they argued that the high turbulence observed in the warm ionized medium (WIM) is likely captured in the cold molecular gas by a mass and energy flow. They characterized this phenomenon as a relation between the gas velocity dispersion and the SFI, $\sigma = \epsilon \sqrt{\Sigma_{\text{SFR}}}$. This relationship is a simple formulation of the coupling (with efficiency, $\epsilon$) between the energy injection into the ISM and the kinetic energy of gas: specifically, $\sigma_{\text{1D}}^2 = \epsilon^2 \Sigma_{\text{SFR}}/3 + \sigma_{\text{0,1D}}^2$, where $\sigma_{\text{0,1D}}$ accounts for dispersions which are not associated directly to star formation (Agertz et al. 2009; Stilp et al. 2013). Stars would then form in a population of molecular clouds with a high relative velocity dispersion embedded in a thick gas disk. Since the stellar population formed out of such gas, it would have a similarly high velocity dispersion and be geometrically thick.

Having estimated the SFI evolution of the MW (Section 2.2), we can use the relation between $\sigma$ and $\Sigma_{\text{SFR}}$ to estimate the dispersion in stellar velocities in the solar neighborhood (Haywood et al. 2013). Such a relation reproduces the trends in the evolution of the dispersions in the $W$-velocity (perpendicular to the plane) and $U$-velocity (radial) components of individual stars in the MW if we adopt $\epsilon = 110$ km s$^{-1}$ (M$_{\odot}$ yr$^{-1}$ kpc$^{-2}$)$^{-1/2}$ and $\sigma_{\text{0,1D}} = 5–10$ km s$^{-1}$ (Figure 3). The coupling efficiency required to explain the MW data is similar to that necessary for the SFI–$\sigma$ relation in high-redshift galaxies (Lehnert et al. 2013). Radial velocities may be affected by secular processes, which will increase the radial motions over time. Thus, the dispersion in the velocities in the radial direction may be taken as an upper limit to the initial dispersion. The vertical velocities may be affected by heating through satellite accretion, for example, but our analysis indicates that the $\sigma$–age relation is close to the initial one and that subsequent dynamical processes perhaps modified it, but did not erase it. The evolution in the dispersion of velocities among stars in the MW is reminiscent of the general decrease in spatially resolved line widths with decreasing redshift observed in high-redshift galaxies (Epinat et al. 2010; Kassin et al. 2012).

We have connected the evolution of the velocity dispersion of the disk stars of the MW to a relationship observed for gas in distant galaxies, but what about the general population of star-forming galaxies over a wide range of redshifts? Since
we cannot typically measure the stellar velocity dispersions of distant disk galaxies, we will use the Hα line widths for this comparison. Similar to the relation between the SFI and the gas velocity dispersion, there is also a relationship between the total SFR and the mean gas velocity dispersion, $\sigma_{\text{mean}}$, in local and distant star-forming galaxies (Green et al. 2010; Lehnert et al. 2013). This relationship is determined using the velocity dispersion and SFR estimated from the width and luminosity of Hα line and it is appropriate for the WIM, not the stars (cf. Figure 3). We demonstrate that the MW was similar to local and distant disk galaxies (Figure 4) if we assume the relationship, $\sigma_{\text{Hα,mean}}^2 = (\epsilon \sqrt{\text{SFR}})^2 + \sigma_{\text{thermal}}^2$ (blue diamonds which represent from left to right, $z = 0.1, 0.3, 0.8, 1.3, 2, 3$). We used a standard relation to convert between total Hα luminosity and SFR for both the local and distant galaxies (appropriately scaled for the IMF; Kennicutt 1998). The gray box shows the range of current SFR and the mean gas velocity dispersion, $\sigma_{\text{mean}}$, for nearby and distant galaxies (Lehnert et al. 2013, and references therein), not necessarily intensely star-forming galaxies from observations sample galaxies with a variety of inclinations and epochs. Models which result in a constant SFR with no significant increase at early times (e.g., Naab & Ostriker 2006), are at odds with what has been inferred for both MW progenitors and the MW itself. The fossil record of the MW and observations of MW progenitor galaxies imply that the formation of the thick disk was a generic process in the growth of disk galaxies and that the thick disk represents the imprint of intense star formation.

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3. DISCUSSION AND CONCLUSIONS

Our results imply that the thickness of the disk in the early evolution of the MW was related to its SFI, total SFR, and the conditions of the ISM. This relationship may be direct in that the mechanical and radiative energy output from the young massive stars may drive a simple energy injection–kinetic energy relationship or it could be indirect in that other processes may contribute, such as gas accretion (but see Hopkins et al. 2013). Such a relation provides a natural explanation as to why the disk is both thick and the stars within it have a high dispersion in velocity and why the oldest stars in the MW show no metallicity gradient. The high turbulence levels weaken any intrinsic metallicity gradients due to the short mixing timescales of the gas.

Our analysis implies a central role for the formation of the thick disk in the evolution of disk galaxies generally: the only way the MW progenitors match the evolution of the MW is through the formation of thick disks during their early evolution. It is the relationship between star formation and turbulence that draws a direct connection between observations of distant galaxies and the inferred evolution of the MW. The formation of the thick disk is simply a reflection of the fact that galaxies are gas rich and have intense star formation in their early evolution and it is the impact of high SFI, which results in the disk being thick, that links the early evolution of the MW to the MW-like galaxy progenitors. Models which result in a constant SFR with no significant increase at early times (e.g., Naab & Ostriker 2006), are at odds with what has been inferred for both MW progenitors and the MW itself. The fossil record of the MW and observations of MW progenitor galaxies imply that the formation of the thick disk was a generic process in the growth of disk galaxies and that the thick disk represents the imprint of intense star formation.

Figure 4. Mean velocity dispersion of the Hα line profile, $\sigma_{\text{mean}}$ (km s$^{-1}$), vs. the integrated SFR ($M_\odot$ yr$^{-1}$) for nearby and distant galaxies (Lehnert et al. 2013; Green et al. 2010). We also indicate, using the SFR of the MW (Snaith et al. 2013), where the MW would lie in the relationship assuming $\sigma_{\text{Hα,mean}} = (\epsilon \sqrt{\text{SFR}})^2 + \sigma_{\text{thermal}}^2$ (blue diamonds which represent from left to right, $z = 0.1, 0.3, 0.8, 1.3, 2, 3$). We used a standard relation to convert between total Hα luminosity and SFR for both the local and distant galaxies (appropriately scaled for the IMF; Kennicutt 1998). The gray box shows the range of current SFR estimated for the MW (1.9 ± 0.4 M_⊙ yr$^{-1}$; Chomiuk & Povich 2011) and velocity dispersions of the Hα line along over 100 lines of sight in the MW (≈20–25 km s$^{-1}$; Haffner et al. 2009).

(A color version of this figure is available in the online journal.)
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