Placing the MW in its Cosmological Context

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Inferring the Formation History of the Disk

- Galaxy formation is still an experimental, observationally-driven field; present-day MW is crucial

- The disk is a messy place. Historically, this has made us as grumpy as Hogg. “Shit Happens” and our view into the past is fundamentally limited.

- Recent results suggest that the Galaxy retains more knowledge of its history than previously thought

- Unbelievably exciting time RIGHT NOW
  - Current and upcoming MW surveys -> unprecedented discriminatory power in the $z=0$ boundary condition
  - We have testable models that capture non-linear process over cosmic time

- Before we go measure $P(\text{model} \mid \text{observations})$, we need to know we are capturing the right physics
The Linked-In Profile of Disk Galaxies

NGC 891 Credit: NASA
The Vertical Structure of the MW

Extragalactic Thick Disks are ubiquitous!

Gilmore & Reid (1983)

Dalcanton & Bernstein (2002); Yoachim & Dalcanton (2006)
The Properties of the MW’s Disk

Local Spectroscopic samples show bifurcation in chemical abundance plane

The Properties of the MW’s Disk

Local Spectroscopic samples show bifurcation in chemical abundance plane

Rich literature showing Chemistry and Kinematics are highly correlated;
c.f. papers by Bensby, Freeman, Gilmore, Nordstrom, Navarro, many others


Lee, …, Bird+ (2011)
Mono-Abundance Populations of the MW
(Bovy 2012 abc)
Smooth Correlation of Chemistry and Kinematics in MW

Point size is indicative of dynamical temperature

\[ [\alpha/Fe] \propto \sigma \]
[alpha/Fe] strongly correlated with age

Are these trends representative of a dynamical history?
MW Age Velocity Relation

Interpretation:

Disk grows over time

Tracer:

Nearby Stars

Fig. 7. Velocity dispersions vs. age for the subsample with $\sigma_{\text{Age}} < 25\%$. The 30 bins have equal numbers of stars (88 in each); the lines show fitted power laws. The 3 youngest and oldest bins were excluded from the fit.

Fig. 8. (a): Observed AVRs with the fitted power law. (b-d): Simulated AVRs for three different disk heating scenarios (see text). Open symbols: derived age and velocity dispersion for the synthetic stars (sampling as in (a); $\sigma_{\text{Age}} < 25\%$).

In GCS II we used simulations to check if our age determination process might change the shape or slope of the AVR. We found this not to be the case when assuming a smooth increase in velocity over the whole lifetime of the disk, consistent with the observed AVR. However, the coarse sampling of the AVR as shown in GCS I (Fig. 31) has led to suggestions that the data might equally well be described by an initial increase in velocity dispersion followed by a plateau. We have explored some of these possibilities through simulations following the recipe in GCS II. A "true" AVR is assumed, after which we computes synthetic "observations" with realistic random errors for a synthetic sample with similar astrophysical parameters as the real sample. The AVR is then reconstructed from the synthetic "observations" in the same manner as for the real data, focusing only on the $W$ component for the reasons discussed by Seabroke & Gilmore (2007).

The results of the simulations are compared to the observations in Fig. 8, panel a repeating the observed $\sigma_W$ from Fig. 7.

The following three cases were considered:

The first synthetic AVR (panel b) is in velocity dispersion over the whole lifetime of the thin disk. However, simulations (Hänninen & Flynn 2002) have shown that if only known local heating agents are assumed (i.e. GMCs), implausible amounts are needed to match the observed $\sigma_W$ for the oldest disk stars.

The second synthetic AVR (panel c) starts out with a smooth $\sigma_W = 18\text{ km s}^{-1}$, then saturates at constant $\sigma_W$. This case is similar to the relation derived by Quillen & Garnett (2001) from the sample of only 189 stars from Edvardsson et al. (1993).

The third assumed AVR (panel d) has a $\sigma_W$ increasing smoothly to $\sim 15\text{ km s}^{-1}$ at an age of 3 Gyr when it rises abruptly to $\sim 21\text{ km s}^{-1}$, then remains constant until the maximum age of the thin disk at 10 Gyr. The scenario here is a late minor merger causing a step increase in $\sigma_W$. After the merger, the local heating processes cease to be effective for the stars formed prior to the merger, and $\sigma_W$ stays flat.

In all three simulations the thick disk appears at the age 11–12 Gyr, with a $\sigma_W$ of 36 km s$^{-1}$ (short horizontal line above the last symbol in Panels b-d).

With the size and other properties of the sample we have analysed, there is a clear qualitative difference between the AVR corresponding to the three scenarios. However, a rigorous Holmberg+ (2009)
$M_{\text{vir}} = 7 \times 10^{11} M_{\odot}$

$R_d \sim 2.4 \text{ kpc}$

$V_{2.2} \sim 240 \text{ km/s}$

High mass/force resolution

Quiet Accretion since $z \sim 3$

Molecular Phase (Christensen+ 2012)
Solar Neighborhood AVR (h277 vs MW)

![Graph showing the relationship between stellar age and velocity dispersion](image)

- **GCS (Casagrande+ 2012)**
- **h277**

Bird+ (2015, in prep.)
Present-day correlation between stellar chemistry and kinematics is strong and smooth.

The physical origin is likely “smooth” as well.

Many contemporary cosmological models qualitatively match trends at $z=0$ (Bird+2013, Stinson+ 2013, Martig+ 2015).

What can we learn? Do more BCs exist?
High Redshift Galaxies show Disk Settling

Tracer: Young Stars

Interpretation: Disk collapses over time

Wisnioski, Forster Schreiber+ (2014)
Our measurements are of intrinsic quantities and therefore are different from the mock observations of e.g., Covington et al. (2010) which take into account myriad observational effects. Our goal is to determine the intrinsic kinematic evolution in the simulations, not to investigate observational effects as in Covington et al. (2010). Median values of $\sigma_g$ and $V_{rot}$ at discrete redshifts for the warm and cold gas in our 4 simulated galaxies are shown in the top panels of Figure 1. Values of these quantities for the individual simulated galaxies are shown in the bottom panels. In the top panels, the median values are compared to those for an observed mass-limited sample of 270 star-forming galaxies from Kassin et al. (2012). Qualitatively, the simulated galaxies follow the same trends as the observations: they increase in $\sigma_g$ and decrease in $V_{rot}$ with increasing redshift over $0 < z < 1$. In other words, both the simulations and the observations decrease in $\sigma_g$ and increase in $V_{rot}$ with time over the last $\sim 8$ billion years, demonstrating that the simulated galaxies undergo the disk settling found in observations. Similarly, Bird et al. (2013) find that the ratio of ordered to disordered motions ($V_{rot}/\sigma_g$) decreases with time for a similar mass galaxy from the Eris simulation. Furthermore, the scatter in $\sigma_g$ and $V_{rot}$ for the warm/cold gas in the individual simulated galaxies is large, similar to the scatter in the observations (Figure 5 in Kassin et al. 2012). As expected, the normalizations of the simulated and observed relations differ. The median values of $V_{rot}$
AVR origin? Gas Settling in h277

![Graph showing vertical velocity dispersion over time and redshift.](image)
Gas Settling in h277

[Graph showing vertical velocity dispersion over time with redshift values.
Vertical Velocity Dispersion on the y-axis.
Time [Gyr] from 4 Gyr ago to 12 Gyr ago.
10 Gyr ago vs. NOW.
]
SF during gas collapse

Bird+ (2013) for U-D Growth
High Redshift Galaxies show Disk Settling

Tracer: Young Stars

Interpretation: Disk collapses over time

Wisnioski, Forster Schreiber+ (2014)
Upside-Down Disk Growth

Vertical Velocity Dispersion vs. Time [Gyr]

Bird+ (2013) for U-D Growth

10 Gyr Ago – Now
In-situ AVR persists, stars still heat after birth
In-situ AVR persists

Bird+ (2013) for U-D Growth

Old Stars

Young Stars

Vertical Velocity Dispersion

Time [Gyr]

10 Gyr Ago

NOW
In-situ AVR persists

Bird+ (2013) for U-D Growth
Star Formation adds Pressure Support to Disk

Star Formation Rate [M$_{\odot}$/Yr]

Galaxy Age [Gyr]

Linear relationship predicted via stability argument (Krumholtz+ 2012)

Bird+ (2015)
Very interesting time: Our tools are crude (very uncertain sub-grid physics) but powerful (able to make testable predictions over cosmic time). Thinking of the MW as a boundary condition on the D.E.s of your formation model is powerful technique.

To match MW AVR: **Disk forms Upside-Down** (old stars born hot) Upside-Down formation only self-consistent model to match both high and low redshift kinematic constraints (analytically anticipated and code-robust)

As z=0 picture becomes clear -> more pressure on models. MW surveys might yield $P(\Theta | 0)$

Bird+ (2013); Bird+ (2015, in prep.)
The APOGEE Footprint

Contact me for getting started guide

“APOGEE: Zero to Hero” (July 2015)

Bovy: apogee python module

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Chemical Cartography of the MW

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With great power comes great responsibility. Modelers must know the data better than ever.

As $z=0$ picture becomes clear -> more pressure on models. MW surveys might yield $P(\Theta | \mathbf{0})$

Bird+ (2013); Bird+ (2015, in prep.)