What drives the kinematic evolution of star-forming galaxies?

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Abstract. One important result from recent large integral field spectrograph (IFS) surveys is that the intrinsic velocity dispersion of galaxies increases with redshift. Massive, rotation-dominated discs are already in place at \( z \sim 2 \), but they are dynamically hotter than spiral galaxies in the local Universe. Although several plausible mechanisms for this elevated velocity dispersion (e.g. star formation feedback, elevated gas supply, or more frequent galaxy interactions) have been proposed, the fundamental driver of the velocity dispersion enhancement at high redshift remains unclear. We investigate the origin of this kinematic evolution using a suite of cosmological simulations from the FIRE (Feedback In Realistic Environments) project. These simulations reproduce the observed trends between intrinsic velocity dispersion (\( \sigma_{\text{intr}} \)), SFR, and \( z \). In both the observed and simulated galaxies, \( \sigma_{\text{intr}} \) is positively correlated with SFR. \( \sigma_{\text{intr}} \) increases with redshift out to \( z \sim 1 \) and then flattens beyond that. In the FIRE simulations, \( \sigma_{\text{intr}} \) can vary significantly on timescales of \( \lesssim 100 \) Myr. These variations closely mirror the time evolution of the SFR and gas inflow rate (\( \dot{M}_{\text{gas}} \)). By cross-correlating pairs of \( \sigma_{\text{intr}} \), \( \dot{M}_{\text{gas}} \), and SFR, we show that the increased gas inflow leads to subsequent enhanced star formation, and enhancements in \( \sigma_{\text{intr}} \) tend to temporally coincide with increases in \( \dot{M}_{\text{gas}} \) and SFR.

1. Introduction
The increasing capabilities of optical and near-infrared integral field spectrographs (IFSs) have revealed the internal dynamics of hundreds of star-forming galaxies out to \( z \lesssim 3 \) (see the review by Glazebrook K [1]). These IFS surveys at \( 1 \lesssim z \lesssim 3 \) reveal that a significant fraction (> 1/3) of massive galaxies (\( M_* \gtrsim 10^{10} M_\odot \)) exhibit smooth velocity gradients, indicative of rotating discs, whereas the rest exhibit irregular, merger-like kinematics or are dispersion-dominated (e.g. [2, 3]). However, a key difference between these massive rotating discs at \( z \gtrsim 1 \) and spiral galaxies in the local Universe is that intrinsic velocity dispersions traced by ionized gas (hereafter \( \sigma_{\text{intr}} \)) of \( z \gtrsim 1 \) systems are significantly higher than those of their local counterparts.

The elevated \( \sigma_{\text{intr}} \) in high-\( z \) galaxies has been associated with enhanced turbulent motions. However, the physical driver(s) of the enhanced turbulence (e.g. feedback or gravitational instability) remains unclear. Lehnert M D show that there is a positive correlation between \( \sigma_{\text{intr}} \) and star formation rate (SFR) surface density in \( z \sim 2 \), possibly suggesting that the enhanced \( \sigma_{\text{intr}} \) is driven by star formation feedback processes such as supernovae and radiation pressure [4, 5]. It has also been claimed that gravitational instabilities due to external sources, such as cosmological gas accretion and galaxy interactions, or internal dynamics, such as disc instabilities and clump-clump interactions, are responsible for the elevated \( \sigma_{\text{intr}} \) exhibited by...
high-z galaxies. Several works have found that the evolution of gas fraction (in a marginally stable disc) can explain the increase in $\sigma_{\text{intr}}$ with $z$ (e.g. [6, 3]).

In this study, we aim to explore the physical drivers of $\sigma_{\text{intr}}$ in star-forming galaxies using a suite of cosmological simulations from the FIRE project [7]. In parallel, we gather measurements of $\sigma_{\text{intr}}$ of star-forming galaxies at $0 \leq z \lesssim 3$ from IFS surveys presented in the literature.

2. A comparison with observations

We compare the kinematic properties of the simulated galaxies from the FIRE project with observations from the literature. Specifically, we examine whether the FIRE simulations exhibit the general trends in $\sigma_{1\text{D}}$, $z$ and SFR present in the observations, and here $\sigma_{1\text{D}}$ is defined as the minimum value of the SFR-weighted standard deviation of the velocity distribution over different viewing angles in the simulations. Figure 1 shows $\sigma_{1\text{D}}$ as a function of redshift. The median $\sigma_{1\text{D}}$ values of the observed galaxies are generally $\sim 10 - 20$ km s$^{-1}$ higher than those of the simulated galaxies. The possible origins of this systematic offset is still under investigation. Regardless, the observed and simulated samples follow a similar trend with redshift, in that the median $\sigma_{1\text{D}}$ increases from $z \sim 0$ to $z \sim 1$ and then remains approximately constant at $z \gtrsim 1$.

Figure 2 shows the distribution of $\sigma_{1\text{D}}$ and SFR for the observed and simulated galaxies. For the observed galaxies, a positive correlation is seen out to $z \lesssim 1$, consistent with the results of Green A W [8]. Although the dynamical range in SFR is smaller for the lower redshift galaxies compared with the higher redshift galaxies, no obvious offset is seen in the $\sigma_{1\text{D}}$-SFR relation within the redshift range probed. However, it becomes less clear whether the same positive correlation extends to $z \gtrsim 2$ galaxies owing to the small number of galaxies. The star-forming galaxies (galaxies that lie on or above the galaxy main sequence) from the FIRE simulations also exhibit a positive correlation between $\sigma_{1\text{D}}$ and SFR, consistent with the observed galaxies, and there is also no obvious offset in this $\sigma_{1\text{D}}$-SFR relations at different redshifts.

Although the FIRE simulations reproduce the observed trends on the $\sigma_{1\text{D}}$-$z$ and $\sigma_{1\text{D}}$-SFR planes, understanding what physical processes are responsible for these trends remains challenging. First, the interpretation that velocity dispersion increases with redshift is tangled with the positive correlation between $\sigma_{1\text{D}}$ and SFR, given that galaxies targeted by IFS surveys at $z \gtrsim 1$ tend to have higher SFRs compared with galaxies targeted by lower-redshift IFS surveys. Second, the $\sigma_{1\text{D}}$ values of the observed galaxies exhibit large scatter even after taking into account the differences in SFR and removing galaxies that fall below the main sequence, suggesting that star formation is not the only relevant driver of velocity dispersion (although this interpretation can be complicated if the SFR and $\sigma_{1\text{D}}$ vary on short timescales and are not perfectly synchronised; this is explored in detail below).

3. Physical drivers of kinematic evolution

To gain further insight into the physical drivers of galaxy dynamics, we analyze the time evolution of various physical properties of the individual central galaxies of each halo. The time evolution of SFR and $M_{\text{gas}}$ most closely resemble the variations in $\sigma_{1\text{D}}$; all three properties vary significantly on timescales of $< 100$ Myr. By definition, $\sigma_{1\text{D}}$ approaches zero at low SFR (SFR $\lesssim 1$ $M_\odot$ yr$^{-1}$), since only few SPH gas particles with non-zero SFRs are available to trace the galaxy dynamics. In general, such time periods also correspond to when galaxies have lower gas inflow rates. Increases in $\sigma_{1\text{D}}$ occur near enhancements in $M_{\text{gas}}$ and SFR, although not exactly simultaneously. The approximate temporal correspondence of variations in $\sigma_{1\text{D}}$ and SFR is reflected in the positive SFR-$\sigma_{1\text{D}}$ correlation, and the fact that peaks do not exactly coincide in time may be responsible for the large scatter in this relation (figure 2). The similarities between the evolutions of SFR, $\sigma_{1\text{D}}$, and $M_{\text{gas}}$ suggest that variations in velocity dispersion, star formation (and thus prompt stellar feedback) and variations in gas inflow are all related.
Figure 1. $\sigma_{1D}$ as a function of redshift. The dark grey solid line shows the median value for the simulated galaxies that lie on or above the star-forming galaxy main sequence within redshift bins of width $\Delta z = 0.5$, and the lighter (lightest) grey coloured area encloses 68 per cent (95 per cent) of the data. The coloured dots and the distribution bars summarize the observations described in Section 3.1; each color represents an IFS survey. In each distribution bar, the middle bar corresponds to the median $\sigma_{1D}$, and the boxes and vertical bars encompass 68 and 95 per cent of the data, respectively. The width of each distribution bar is proportional to the redshift coverage of the survey. The black crosses represent the median $\sigma_{1D}$ of the observed galaxies that fall on or above the galaxy main sequence in six redshift bins: $z < 0.1$, $0.1 < z < 0.3$, $0.7 < z < 1.0$, $1.0 < z < 1.5$, $2.0 < z < 2.5$, and $3.0 < z < 3.5$. The simulated and observed galaxies exhibit the same qualitative trend, i.e. the median $\sigma_{1D}$ increases from $z = 0$ to $z \sim 1$ and then remains constant, but at a given redshift, the simulated galaxies have median $\sigma_{1D}$ values $\sim 10 - 20$ km s$^{-1}$ less than the observed galaxies.

To examine whether the similarities in the temporal evolutions of SFR, $\sigma_{1D}$, and $\dot{M}_{\text{gas}}$ are indicative of any causal effects, we measure the time delays between pairs of these three quantities by cross-correlating their time series. For each simulation suite, we calculate temporal cross-correlation functions of pairs of time series $[(x, y) = (\dot{M}_{\text{gas}}, \text{SFR}), (\dot{M}_{\text{gas}}, \sigma_{1D})$, and $(\sigma_{1D}, \text{SFR})]$ that are normalised to have means of 0 and variances of 1, $\text{CCF}(\tau_k) = \frac{1}{N} \sum_{i=1}^{N-k} x_i y_{i+k}$, where $i$ indicates the time bin, $N$ is the total number of time bins, $\tau_k$ is the lag corresponding to the $k$ time bin, and $k$ is varied to probe lags from $-500$ to 500 Myr.

In general, variations in $\dot{M}_{\text{gas}}$ occur prior to variations in the SFR, suggesting that inflows through $0.2 R_{\text{vir}}$, due to cosmological gas inflow or galactic fountains, lead to subsequent enhanced star formation activity. As expected, the relation between $\dot{M}_{\text{gas}}$ and SFR becomes weaker if we define the inflow rate as the mass infalling through a shell with a radius of $1 R_{\text{vir}}$. The negative signs of $\tau(\dot{M}_{\text{gas}}-\sigma_{1D})$ or $\tau(\sigma_{1D}-\text{SFR})$ are measured in a few simulation suites, suggesting that enhancements in velocity dispersion may occur after enhancements in the gas inflow rate at $0.2 R_{\text{vir}}$ but before the SFR is enhanced. However, these trends are less robust because positive or zero time delays are also detected for some simulation suites.
Figure 2. Distribution of observed and simulated galaxies on the $\sigma_{1D}$–SFR plane, colored-coded according to redshift. The open circles in the observations panel indicate galaxies that fall below the galaxy main sequence. The black x’s and error bars overlaid on the data points represent the median $\sigma_{1D}$ and 68 per cent distribution of the galaxies that lie on or above the main sequence in four log(SFR) bins. The simulations and observations both exhibit correlations between $\sigma_{1D}$ and SFR, but at fixed SFR, except for the highest-SFR bin, the simulations have $\sigma_{1D}$ values $\sim 20$ km s$^{-1}$ less than the observed galaxies.

Given that the absolute values of $\tau(\dot{M}_{\text{gas}}-\sigma_{1D})$ and $\tau(\sigma_{1D}\text{-SFR})$ are typically smaller than the resolution of the times series, we can only conclude that variations in $\sigma_{1D}$ temporally coincide with variations in $\dot{M}_{\text{gas}}$ and SFR.

References
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