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Falling outer rotation curves of star-forming galaxies at 0.7 <z< 2.6 probed with KMOS^{3D} and SINS/zC-SINF

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Abstract. We exploit the deep Hα IFU kinematic data from the KMOS^{3D} and SINS/zC-SINF surveys to explore the so far unconstrained outer rotation curves of star-forming disk galaxies at high redshift. Through stacking the signal of $\sim$ 100 massive disks at $0.7 < z < 2.6$, we construct a representative rotation curve reaching out to several effective radii. Our stacked rotation curve exhibits a turnover with a steep falloff in the outer regions, significantly strengthening the tantalizing evidence previously hinted at in a handful only of individual disks among the sample with the deepest data.

This finding confirms the high baryon fractions found by comparing the stellar, gas and dynamical masses of high redshift galaxies independently of assumptions on the light-to-mass conversion and Initial stellar Mass Function (IMF). The rapid falloff of the stacked rotation curve is most naturally explained by the effects of pressure gradients, which are significant in the gas-rich, turbulent high-z disks and which would imply a possible pressure-driven truncation of the outer disk.

Keywords. galaxies: evolution - galaxies: kinematics and dynamics - galaxies: high-redshift

1. Introduction

Rotation curves (RCs) are a key probe to disentangle the baryonic versus dark matter (DM) components of disk galaxies at different radii. Observations of nearby disk galaxies have shown that their extended RCs are flat (e.g. Sofue & Rubin 2001, and references therein) due to the imprint of the dominant DM component in the outer parts ($R > 2R_e$, e.g. Courteau & Dutton 2015).

At higher redshifts, deep IFU surveys such as KMOS^{3D} have enabled us to systematically study the ionized gas kinematics and RCs of massive star-forming galaxies (SFGs) based on large ($\sim$ 600) samples. The surface brightness limitation inherent to observations of galaxies at high redshift currently only allow to trace RCs in the inner parts ($\lesssim 2R_e$), while their extended outer shapes remain largely unconstrained. Comparing estimates on the stellar + gas mass with (inner) dynamical profiles, studies found that SFGs at $z \sim 1-3$ appear to be strongly baryon dominated in their inner parts (e.g. Burkert *et al.* 2015, Wuyts *et al.* 2016). These high baryonic fractions likely leave an imprint on their outer rotation curves. Indeed, few individual galaxies with very deep integrations from the e.g. SINS/zC-SINF AO survey exhibit dropping rotation curves (Förster Schreiber *et al.* 2006; Genzel *et al.* 2008, 2014a). Here, we want to further test if such a behavior is typical for massive star-forming galaxies at high redshift. Due to the sharply

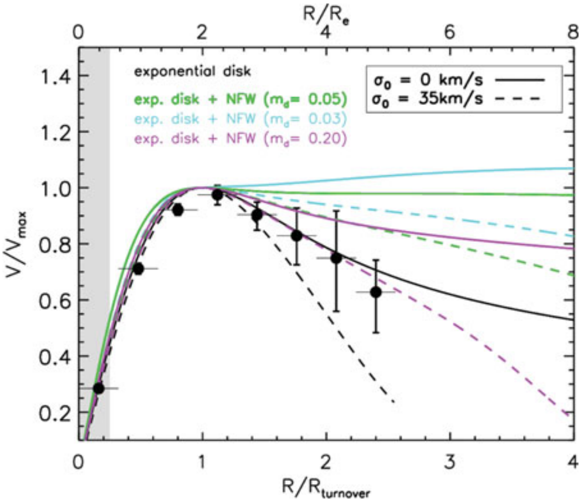

Figure 1. Stacked rotation curve in normalized coordinates, shown together with models representing a rotating exponential disk (black), and added dark matter NFW halos for different disk mass fractions m_d. The dashed (and solid) lines represent models with pressure support in the outer disk assuming $\sigma_0 = 35$ km/s (and with no pressure support, respectively). The grey area marks the HWHM of the average PSF, which has been accounted for in the models.

dropping Hα surface brightness with galactocentric radius, we approach this by stacking the extensive set of available IFU data from the combined deep SINS/zC-SINF AO and the more recently started KMOS^{3D} survey. The combination of those datasets provides a unique synergy of data quality and sample size, suitable for constraining the outer disk kinematics of galaxies with a good coverage of the $SFR - M_*$ plane at $0.7 < z < 2.6$.

2. Results

Figure 1 shows our current results on stacking rotation curves of massive SFGs at high redshift, with further analysis being in progress. The stacked RC is plotted as a function of normalized coordinates V_{max} and R_{turn} (i.e. the turn-over radius as expected from a rotating exponential disk model), together with an estimate on the corresponding intrinsic radius in units of intrinsic R_e. Currently, the stack includes 101 star-forming disks selected from the set of detected and spatially resolved KMOS^{3D} and SINS/zC-SINF targets, yielding a representative subset of massive ($M_* \gtrsim 10^{10} M_\odot$) SFGs at $0.7 < z < 2.6$.

As apparent from Figure 1, our stacking approach enables us for the first time to constrain a representative RC reaching out well beyond the turn-over radius, out to several effective radii. Our stack exhibits a sharp drop of rotation velocity beyond R_{turn}. Individual deep integrations of a few massive SFGs within the SINS/zC-SINF AO survey show a similar drop of rotation velocity at these radii (e.g. Genzel *et al.* 2014a). Based on our stack, however, this behavior seems to be a common feature for our sample of massive SFGs at high redshift.

The fall-off in our stack appears to be clearly distinct from the flat or mildly rising RCs of local massive spirals at the same galactocentric radii (e.g. Catinella *et al.* 2006). To interpret the outer shape of our RC, we compare our data to axisymmetric models that include rotating exponential baryonic disks and NFW halos, adopting a range of mass fractions of the disk relative to the halo inside the virial radius, $m_d = M_{Baryons}/M_{DM}$. The models take into account the redshift evolution of the halo concentration c (with c

being $4 - 6$, depending on halo mass, e.g. Bullock *et al.* 2001) and the level of spatial beam smearing affecting our data. The range of models tested ($m_d \sim 0.03$ for $z \sim 0$ MW-like halos, $m_d \sim 0.05$ as an estimate for massive high-z SFGs galaxies, see Burkert *et al.* 2015, and $m_d \sim 0.2$ as an upper limit representing the *cosmic* baryonic fraction) all show a poor fit the data.

However, as high-z SFGs exhibit elevated levels of intrinsic velocity dispersion σ_0 (e.g. Förster Schreiber *et al.* 2006, Wisnioski *et al.* 2015) as measured in their outer disks, it is important to take into account the resulting pressure support to the disk. Considering an average, radially constant velocity dispersion of $\sigma_0 = 35$ km/s, the models (represented by the dashed lines in Figure 1) can be brought into much better agreement with the data within the uncertainties. Our current analysis indicates that when considering galaxies with strong pressure support (represented by targets with *low* V_{rot}/σ_0) for stacking, the resulting outer RC steepens compared to when selecting galaxies with *high* V_{rot}/σ_0, which supports the conclusion that at least part of the fall-off in the stacked RC is driven by the presence of pressure effects in the outer disk.

These results independently confirm that massive star-forming disk galaxies are strongly baryon dominated compared to their local counterparts. Moreover, our analysis indicates that the intrinsic gas velocity dispersion σ_0 persists to the outer disk regions. Interestingly, this finding implies a possible pressure-driven truncation of the outer disk, as observed for some local spirals (e.g. van der Kruit & Freeman 2011). We furthermore show that the above results are largely independent of our model assumptions such as the presence or absence of a stellar bulge, the halo concentration parameter c, and the possible effect of adiabatic contraction of the halo.

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