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Abstract

Using ALFALFA H I data, we investigate the relationship between specific star formation rate (sSFR) and halo spin across a broad sample of star-forming galaxies. Our analysis reveals a weak yet statistically significant positive correlation between sSFR and halo spin, largely independent of galactic environment. This trend indicates that galaxies with higher spin parameters tend to host dynamically colder, gas-rich disks, which maintain elevated gas surface densities and sustain star formation over extended timescales. These results are consistent with theoretical expectations of angular-momentum-regulated gas accretion, but they also expose tensions with cosmological simulations, highlighting persisting challenges in modeling baryonic feedback and star formation efficiency.

Full Text

Preamble

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Quantifying the Relationship between Galaxy Specific Star Formation Rate and Halo Spin for Star-forming Galaxies

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Abstract

Utilizing ALFALFA H I data, we investigate the relationship between specific star formation rate (sSFR) and halo spin across various star-forming galaxies. Our analysis reveals a weak yet statistically significant positive correlation between sSFR and halo spin, irrespective of the galactic environment. This trend suggests that galaxies with higher spin parameters tend to host dynamically colder, gas-rich disks, sustaining elevated gas surface densities and prolonged star formation. These findings align with theoretical expectations of angular momentum-regulated gas accretion but highlight discrepancies with cosmological simulations, underscoring unresolved challenges in modeling baryonic feedback and star formation efficiency.

Key words: galaxies: statistics –galaxies: evolution –galaxies: formation

1. Introduction

In the standard galaxy formation model, halo spin is considered pivotal in galaxy formation and evolution, influencing morphology and regulating baryonic fraction [?, ?, ?, ?, ?, ?, ?, ?]. However, hydrodynamical simulations [?, ?, ?, ?] have sparked debate on the role of halo spin in low-mass galaxies. For most dwarf galaxies, stellar distributions may be independent of or weakly dependent on halo spin, with concentrations and baryonic feedback exerting more significant influence on low-mass galaxy properties. Halos with shallower potential wells and lower concentrations exhibit stronger feedback effects, leading to reduced star formation efficiencies, lower stellar mass fractions, and more extended stellar distributions [?, ?, ?, ?, ?, ?]. Despite extensive research, the influence of halo spin on galaxy structure and evolution remains incompletely understood and lacks consensus.

The star formation rate (SFR), a crucial parameter defining galaxy evolutionary state, is influenced by internal factors such as gas supply, metallicity, and dust content [?, ?, ?, ?]. Environmental factors also play a significant role in shaping the SFR [?, ?]. Among the myriad of galaxy properties, the impact of halo properties on the SFR, while not direct, is paramount. Halos' mass and surface density (SD) have been shown to significantly affect SFRs in galaxies [?, ?], yet the influence of halo spin on SFR remains uncertain. Rong et al. (2024b) propose a link between spin and SFR, suggesting that increased halo spin could hinder gas accretion and slow star formation processes. However, this proposed scenario requires further investigation.

H I surveys conducted with single-dish telescopes, such as the Arecibo Legacy

Fast Alfa Survey (ALFALFA; [?, ?]) and the ongoing FAST All Sky H I survey [?], provide valuable H I spectra from numerous star-forming galaxies. These surveys offer crucial dynamical information on galaxies, facilitating the estimation of spin parameters for galaxies with varying SFRs and enabling the study of halo spin' s impact on SFR.

In this study, we utilize a semi-analytic approach to estimate halo spin for each H I-bearing galaxy cataloged in ALFALFA and investigate the relationship between halo spins and stellar densities of galaxies. Section 2 introduces the sample data and outlines the methodology for estimating halo spin. Section 3 presents a statistical analysis of the dependence of galaxy stellar densities on halo spins. Our findings are summarized in Section 4.

2.1. Sample and Specific Star Formation Rate

We draw our galaxy sample from ALFALFA, a comprehensive H I survey covering 6600 $\deg^2$ at high Galactic latitudes. The ALFALFA (α.100; [?]) catalog, released by Haynes (2018), includes $ 31, 500sourceswithradialvelocitiesbelow18, 000kms^{-1}.Foreachsource, thecatalogprovidestheHIspectrumsignal−to−noiseratio(SNR), cosmologicaldistance, 50
among other properties.

We match ALFALFA galaxies with MPA-JHU DR7 SDSS measurements to obtain SFRs [?] and stellar mass (M_*) based on photometric fits. The specific SFR (sSFR) for each galaxy is then calculated as $\mathrm{sSFR} = \mathrm{SFR}/M_*$ (yr^{-1}). To focus on star-forming galaxies, we select those with $\log(\mathrm{sSFR}) > -11$ [?], where $t_H(z = 0)$ represents the Hubble time at redshift 0.

After applying these selection criteria, our sample comprises 15,787 star-forming galaxies, consisting of 8,187 low-mass ($M_* < 10^{9.5} M_\odot$) systems and 7,600 high-mass ($M_* > 10^{9.5} M_\odot$) counterparts. As illustrated in panel (a) of Figure 1, the vast majority of these galaxies lie on the star-forming main sequence [?, ?], confirming their actively star-forming nature. Panel (b) of Figure 1 presents the stellar mass distribution of the selected sample.

2.2. Rotation Velocity and Halo Spin

The rotation velocity is given by $V_{\mathrm{rot}} = W_{50}/(2 \sin i)$, with inclination i of the H I disk estimated via the optical axis ratio b/a (from [?]) and q_0, setting $i = 90^\circ$ for $b/a \leq q_0$. We assume $q_0 \sim 0.2$ for massive galaxies and $q_0 \sim 0.4$ [?] for low-mass galaxies ($M_* < 10^{9.5} M_\odot$). We exclude galaxies with $i < 50^\circ$ or low SNR (< 10) to ensure accurate V_{rot} measurements.

Some H I-bearing galaxies exhibit velocity dispersion-dominated kinematics. These galaxies, identified by their H I line profiles exhibiting a "single-horned" shape [?], pose challenges in accurately estimating rotation velocities and, consequently, halo spins. Following Hua et al. (2025a), we employ the kurtosis parameter $k_4 < -1.0$ to restrict our analysis to robust subsets of galaxies with double-horned H I profiles to exclude potential contamination from dispersion-dominated systems. After applying all selection criteria, our final sample comprises 2,957 star-forming galaxies.

Assuming an isothermal halo model with negligible baryonic gravitational influence, the halo spin parameter λ_h is estimated as [**?**]:

$$\lambda_h = \frac{2R_{\mathrm{HI,d}} V_{\mathrm{rot}}}{\sqrt{GM_h}}$$

where $R_{\mathrm{HI,d}}$ is the H I disk scale length, derived from:

$$R_{\mathrm{HI,d}} = \frac{r_{\mathrm{HI}}}{1.68}$$

where $\Sigma_{\mathrm{HI,0}}$ is the central SD of the H I disk. The total H I mass M_{HI} is linked to the scale length as:

$$M_{\mathrm{HI}} = 2\pi\Sigma_{\mathrm{HI,0}} R_{\mathrm{HI,d}}^2$$

Additionally, we introduce the H I radius r_{HI}, defined as the radius at which the H I SD reaches 1 $M_\odot$ pc^{-2}. r_{HI} is calculated using the observed r_{HI}-M_{HI} relation [**?**, **?**]:

$$\log\left(\frac{r_{\mathrm{HI}}}{\mathrm{kpc}}\right) = 0.51\log\left(\frac{M_{\mathrm{HI}}}{M_\odot}\right) + 3.59$$

Therefore, at r_{HI}, we have:

$$\Sigma_{\mathrm{HI}}(r_{\mathrm{HI}}) = \Sigma_{\mathrm{HI,0}} \exp\left(-\frac{r_{\mathrm{HI}}}{R_{\mathrm{HI,d}}}\right) = 1\, M_\odot\, \mathrm{pc}^{-2}$$

By using Equations (3) and (4), we can compute the value of $R_{\mathrm{HI,d}}$ for each galaxy in our sample, thereby enabling the estimation of the halo spin.

3. Results

Panels (a) and (b) of Figure 2 illustrate the sSFR–halo spin relation for low-mass ($M_* < 10^{9.5} M_\odot$) and high-mass ($M_* > 10^{9.5} M_\odot$) galaxies. Correlation analysis demonstrates a statistically significant, albeit weak, dependence of sSFR on halo spin, with correlation coefficients of $CC \approx 0.2$ and $CC \approx 0.1$ for the low-mass and high-mass regimes, respectively. The robustness of this trend is underscored by low p-values ($p = 2 \times 10^{-19}$ and $p = 1 \times 10^{-3}$ for the low-mass and high-mass subsamples, respectively), confirming that the correlation, while modest in strength, is highly significant in both regimes. Notably, the relationship seems to be more pronounced in low-mass systems, plausibly suggesting a stronger coupling between halo spin and star formation efficiency in dwarf galaxies compared to their more massive counterparts.

Since environment also affects galaxy properties [**?**, **?**, **?**, **?**, **?**, **?**], we control for environmental influences by using the galaxy group catalog by Saulder et al. (2016), applying a friends-of-friends algorithm to SDSS DR12 [?] and 2MASS Redshift Survey data [?], adjusted for biases (e.g., Malmquist bias). The analysis of 2,245 isolated galaxies—defined as systems located beyond three virial radii from any galaxy group—reveals a consistent, albeit weak, correlation between sSFR and halo spin (Figure 2, panels (c) and (d)). Statistically significant trends are observed for both low-mass ($CC = 0.22$, $p = 2 \times 10^{-14}$) and high-mass ($CC = 0.14$, $p = 3 \times 10^{-6}$) subsamples.

4. Discussion and Conclusion

Using ALFALFA H I data, we examine sSFR–halo spin relationships for a range of star-forming galaxies. Our analysis reveals a weak but statistically significant correlation between them, independent of environment. Notably, star-forming main sequence galaxies exhibit increasing sSFR with higher spin parameters, with this trend being more pronounced in low-mass systems compared to their high-mass counterparts.

To ensure the robustness of this finding, we conducted multiple validation tests. First, we examine the sSFR-spin correlation across multiple inclination thresholds (30°, 40°, 60°, and 70°). As shown in Figure 3, the statistically significant correlation persists at all tested inclination angles, despite showing relatively weak correlation coefficients ($0.1 < CC < 0.3$). This demonstrates that our results are robust against potential inclination-related biases in the H I kinematic measurements. Second, to verify the methodology dependence, we also recompute the spin parameter using stellar disk scale lengths ($R_{*,d}$) instead of H I scale lengths ($R_{\mathrm{HI,d}}$) with Equation (1). The stellar scale lengths are derived from effective radii (R_e) following $R_{*,d} \simeq R_e/1.678$ [?], where R_e values are taken from our previous work [?]. While this alternative approach maintains the sSFR–spin correlation (Figure 4), the reduced sample size (due to limited R_e measurements for many ALFALFA galaxies) results in larger p-values and weaker statistical significance.

Third, given the established correlation between surface brightness/density and halo spin [?, ?], we must consider whether the observed sSFR–spin correlation could be artificially induced by sample incompleteness at the high-spin end—where galaxies with low surface brightness/density may be underrepresented [?]. To test this possibility, we split the star-forming galaxy sample into two equal-size subsamples based on stellar SD using measurements from Rong et al. (2025), and examine the sSFR–spin relationship independently for both low-SD and high-SD subsamples. As illustrated in Figure 5, both subsamples retain a significant correlation between sSFR and λ_h, demonstrating that the observed trend is intrinsic rather than an artifact of observational biases.

Finally, building upon the established correlation between H I-to-stellar mass ratio and halo spin [?], we further test the intrinsic nature of the sSFR–spin relationship by dividing our isolated star-forming sample into H I-rich and H I-poor subsamples of equal size. Crucially, both subsamples maintain a statistically significant correlation between sSFR and λ_h (Figure 6). This robust confirmation suggests that the sSFR–spin connection reflects fundamental galactic physics rather than secondary dependencies on H I mass fraction. Our results show excellent agreement with previous findings from MaNGA IFU data [?], confirming the existence of an sSFR–spin correlation in observational data.

However, this relationship is notably absent in the IllustrisTNG50 cosmological simulation [?], where we find no significant correlation between sSFR and λ_h for isolated star-forming galaxies at $z \sim 0$. Figure 7 shows the sSFRs (calculated within $2R_e$) versus λ_h (estimated with the same method of Rodriguez-Gomez 2022) for galaxies. The weak correlation strength ($CC \sim 0$) and high p-values suggest that current simulations may not fully capture the complex baryonic physics governing this relationship, particularly in their treatment of star formation thresholds and feedback mechanisms.

The observed positive correlation between halo spin and sSFR may be understood through several physical mechanisms. Galaxies residing in high-spin halos naturally develop more extended, dynamically colder gaseous disks [?, ?]. These morphological characteristics plausibly promote two key conditions for enhanced star formation: (1) elevated gas SDs that exceed formation thresholds, and (2) prolonged gas local reservoirs that sustain star formation over extended timescales [?, ?]. Recent studies [?, ?] provide empirical support for this scenario, demonstrating that high-spin halos indeed host more extended disks with greater gas fractions. The stronger spin–sSFR correlation in low-mass galaxies likely reflects their dominant cold-mode accretion [?]. In these systems, the star formation efficiency becomes especially sensitive to angular momentum transport and disk stability [?] as their shallower potential wells are less effective at thermalizing incoming gas flows.

While our analysis demonstrates a clear sSFR–spin correlation in typical star-forming galaxies, we note an important exception: isolated ultra-diffuse galaxies (UDGs). Although UDGs are theoretically predicted to possess high halo spins [?], they consistently exhibit suppressed SFRs [?]. This apparent contradiction can be reconciled by considering that UDGs represent a rare population [?] with distinct evolutionary pathways, and that our sample selection criteria explicitly excluded low-sSFR systems, including UDGs. It is worth noting that the sSFR–spin correlation appears to be valid only for actively star-forming galaxies.

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