Halo Spin Dependence on Environment for H i-bearing Galaxies (Postprint)

Authors: Zichen Hua, Yu Rong, and Huijie Hu

Date: 2025-05-09T00:00:00+00:00

Abstract

Leveraging the semi-analytic method, we compute halo spins for a substantial sample of H i-bearing galaxies observed in the Arecibo Legacy Fast ALFA Survey. Our statistical analysis reveals a correlation between halo spin and environment, although the trend is subtle. On average, galaxies exhibit a decreasing halo spin tendency in denser environments. This observation contrasts with previous results from N-body simulations in the Lambda Cold Dark Matter framework. The discrepancy may be attributed to environmental gas stripping, leading to an underestimation of halo spins in galaxies in denser environments, or to baryonic processes that significantly alter the original dark matter halo spins, deviating from previous N-body simulation findings.

Full Text

Preamble

Research in Astronomy and Astrophysics, 25:041001 (5pp), 2025 April https://doi.org/10.1088/1674-4527/adbea1 CSTR: 32081.14.RAA.adbea1

Halo Spin Dependence on Environment for H I-bearing Galaxies

Zichen Hua[1],[2], Yu Rong[1],[2], and Huijie Hu[3]

[1] Department of Astronomy, University of Science and Technology of China, Hefei 230026, China; rongyua@ustc.edu.cn

[2] School of Astronomy and Space Sciences, University of Science and Technology of China, Hefei 230026, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China

Received 2024 November 11; revised 2024 November 15; accepted 2025 March 7; published 2025 April 9

Abstract

Leveraging the semi-analytic method, we compute halo spins for a substantial sample of H I-bearing galaxies observed in the Arecibo Legacy Fast ALFA Survey. Our statistical analysis reveals a correlation between halo spin and environment, although the trend is subtle. On average, galaxies exhibit a decreasing halo spin tendency in denser environments. This observation contrasts with previous results from N-body simulations in the Lambda Cold Dark Matter framework. The discrepancy may be attributed to environmental gas stripping, leading to an underestimation of halo spins in galaxies in denser environments, or to baryonic processes that significantly alter the original dark matter halo spins, deviating from previous N-body simulation findings.

Key words: galaxies: halos –galaxies: evolution –galaxies: statistics

1. Introduction

In the context of Lambda Cold Dark Matter cosmology, it is typically assumed that the distributions of galaxies/baryons reflect the distributions of dark matter. Gas is accreted into self-bound, virialized dark matter halos, where it undergoes cooling primarily through radiation and condenses into the central regions of the halos, eventually transforming into stars to give rise to galaxies. The dark matter halo plays a pivotal role in galaxy formation by providing the gravitational potential for gas condensation, serving as a stage for shock-heating gas, and contributing to galaxy rotation through its spin.

Halo spin has significant implications for galaxy evolution and morphology. Hydrodynamical simulations (e.g., Kim & Lee 2013) and semi-analytic galaxy formation models (e.g., Mo et al. 1998) indicate that halo spin strongly influences the size and density of baryonic matter distribution, especially in massive late-type galaxies. While the role of halo spin in low-mass galaxies remains debated, studies on specific dwarf galaxies, such as ultra-diffuse galaxies (Amorisco & Loeb 2016; Rong et al. 2017; Liao et al. 2019; Benavides et al. 2023), suggest that halo spin may significantly impact the distribution of baryonic matter in dwarf galaxies.

Halo spin is believed to arise from tidal torques exerted by large-scale structures, resulting from gravitational interactions with neighboring structures (e.g., Peebles 1969; White 1984), or through mergers (e.g., Gardner 2001; Maller et al. 2002; Vitvitska et al. 2002; Hetznecker & Burkert 2006). As halos approach the turnaround stage between linear and nonlinear phases and eventually reach virialization, the influence of tidal torque diminishes. During this phase, the flow field surrounding halos exhibits non-zero vorticity, crucial in determining halo angular momentum and leading to alignment between halo spin and vorticity (e.g., Libeskind et al. 2013). Notably, halo spin is influenced by the surrounding environment (Hahn et al. 2007a, 2007b; Wang & Kang 2017, 2018). Simulation studies indicate that halos tend to spin faster in stronger tidal fields, with a more pronounced effect observed in more massive halos (Wang et al. 2011). Understanding dark matter halo spin is essential for unraveling the formation and evolution of galaxies in the universe.

However, determining halo spin is a challenging task observationally. Typically, it is estimated by analyzing the velocity fields of stellar or gas components (e.g., Rong et al. 2018; Wang et al. 2020). Presently, only a limited number of high surface brightness galaxies have spatially resolved data with high signal-to-noise ratios (SNRs) suitable for halo spin calculations. Alternatively, broad H I surveys conducted with single-dish telescopes, such as the comprehensive Arecibo Legacy Fast ALFA Survey (ALFALFA; Giovanelli et al. 2005; Haynes et al. 2018) and the ongoing FAST All Sky H I survey (FASHI; Zhang et al. 2024), offer a valuable opportunity to acquire H I spectra from numerous galaxies. These surveys provide essential dynamical information on galaxies, allowing for the estimation of spin parameters across a large galaxy sample and enabling comparisons of rotational speeds in diverse environments.

In this investigation, we employ a semi-analytic approach to estimate halo spin for each H I-bearing galaxy cataloged in ALFALFA. Section 2 presents the sample data and outlines the methodology for estimating halo spin. Section 3 offers a statistical comparison of galaxy halo spins in different environments and discusses the outcomes. Our findings are summarized in Section 4.

2. Methodology

2.1. Sample

The galaxy sample is drawn from ALFALFA, an extensive extragalactic H I survey spanning approximately 6600 deg^2 at high Galactic latitudes. The ALFALFA collaboration has released a fully comprehensive catalog (α.100; Haynes et al. 2018) comprising around 31,500 sources with radial velocities below 18,000 km s^{-1}. This catalog includes various properties for each source, such as the SNR of the H I spectrum, cosmological distance, 50% peak width of the H I line (W_{50}) corrected for instrumental broadening, and the H I mass (M_H I), among others. For detailed definitions of these parameters (and their uncertainties) and the estimation method, we direct readers to Haynes et al. (2018).

2.2. Stellar Mass

ALFALFA galaxies have been matched with Sloan Digital Sky Survey (SDSS) data (Alam et al. 2015). Previous studies by Durbala et al. (2020) have estimated the stellar masses M_* of ALFALFA galaxies with optical counterparts using three ultraviolet-optical-infrared methods: spectral energy distribution (SED) fitting, SDSS $g - i$ color, and infrared W2 magnitude. This study prioritizes the stellar mass derived from SED fitting. In cases where UV or infrared data are unavailable for SED fitting, the stellar mass based on $g - i$ color is utilized. Any discrepancies in stellar mass obtained from these methods are deemed insignificant.

It is important to note that "dark galaxies," a subset of ALFALFA galaxies without optical counterparts or displaying faint optical signatures, have been excluded from this study. These "dark galaxies," as described by Disney (1976) and Janowiecki et al. (2015), are known to be prone to tidal interactions (Duc & Bournaud 2008; Román et al. 2021), making them non-equilibrium systems and leading to inaccurate estimates of rotation velocities.

2.3. Rotation Velocity

The rotation velocity is calculated as V_{rot} = $W_{50}/(2 \sin i)$, where i represents the inclination of the H I disk. In cases where resolved H I data are unavailable, this study utilizes the optical apparent axis ratio b/a, as provided by Durbala et al. (2020), to estimate the H I disk inclination i. The calculation is done using $\cos^2 i = [(b/a)^2 - q_0{}^2]/(1 - q_0{}^2)$ (if $b/a \leq q_0$, we set $i = 90°$), with the intrinsic thickness q_0 0.2 (Giovanelli et al. 1997; Tully et al. 2009; Li et al. 2022) for massive galaxies, and q_0 0.4 (Rong et al. 2024b) for low-mass galaxies with M_* < $10^{9 \cdot 5}$ M_ .

To enhance the accuracy of rotation velocity estimation, galaxies with inclinations $i < 50°$ are excluded. Additionally, galaxies with low H I SNRs (SNR < 20) are also excluded due to significant uncertainties in velocity estimation. As a result, a sample of approximately 7600 galaxies is obtained. The stellar masses of our sample range from around 10^7 to 10^{11} M_ , as illustrated in panel (a) of Figure 2 [Figure 2: see original paper].

2.4. Halo Spin

Theoretical considerations, assuming a galaxy' s dark matter halo follows the isothermal sphere model and neglecting the gravitational impact of baryonic matter, allow us to express the galaxy' s halo spin as (Hernandez et al. 2007)

$$\lambda_h = \frac{V_{\rm rot} R_{\rm H\ I,\mathit{d}}}{G M_{\rm vir}}$$

Here, V_{rot} denotes the halo' s rotation velocity. The scale length of the H I disk, R_H I,d, can be determined by assuming a relatively thin gas disk in centrifugal balance (Mo et al. 1998), characterized by an exponential surface density profile

$$\Sigma_{\rm H\ I}(R) = \Sigma_{\rm H\ I,0} \exp(-R/R_{\rm H\ I,\mathit{d}})$$

where Σ_H I,0 is the central surface density of the H I disk. The total H I mass M_H I is linked to the scale length as

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

Additionally, we introduce the H I radius r_H I, defined as the radius at which the H I surface density reaches 1 M_ pc^{-2}. The estimation of r_H I is guided by the observed correlation between r_H I and H I mass M_H I, as indicated by empirical studies:

$$\log(r_{\mathrm{H\ I}}) = 0.51\log(M_{\mathrm{H\ I}}) - 3.32$$

(Wang et al. 2016; Gault et al. 2021). Therefore, at r_H I, we have

$$\Sigma_{\mathrm{H\ I}}(r_{\mathrm{H\ I}}) = \Sigma_{\mathrm{H\ I},0}\exp(-r_{\mathrm{H\ I}}/R_{\mathrm{H\ I},d}) = 1\ \mathrm{M}_{\odot}\mathrm{pc}^{-2}$$

By utilizing Equations (3) and (4), we can compute the value of R_H I,d for each galaxy in our sample, thereby enabling the estimation of the halo spin.

2.5. Environment

To assess the environmental context of each galaxy in our sample, we utilize the galaxy group and cluster catalog developed by Saulder et al. (2016). This catalog, derived from the SDSS DR12 (Alam et al. 2015) and 2MASS Redshift Survey (Huchra et al. 2012), employs the friends-of-friends group finder algorithm. Notably, the work by Saulder et al. (2016) meticulously addresses various observational biases, including the Malmquist bias and the "Fingers of God" effect.

For environmental classification of galaxies, we adopt the criteria outlined by Rong et al. (2024a). Specifically, galaxies are deemed isolated if they reside beyond three times the virial radius of any galaxy group or cluster. Conversely, galaxies failing to meet this criterion are classified as non-isolated. In Figure 1 [Figure 1: see original paper], we show the optical images of four example sample galaxies located in different environments (isolated and non-isolated) and with different stellar masses (low-mass and high-mass).

3. Results and Discussion

In panel (a) of Figure 3 [Figure 3: see original paper], we present a comparison of the halo spin distributions between isolated galaxies (blue histograms) and non-isolated galaxies (red histograms). Our analysis reveals a slight decrease in halo spins for galaxies located in denser environments. The results of the Kolmogorov-Smirnov (K-S) test further validate distinct halo spin distributions between the two subgroups across various environmental conditions. Specifically, the median halo spin of non-isolated galaxies is approximately 0.02 lower than that of isolated galaxies. This spin discrepancy may stem from environmental gas stripping, as the H I masses of non-isolated galaxies are statistically lower than those of their isolated counterparts (panel (c) of Figure 2), or potentially due to baryonic processes significantly altering the original dark matter halo spins, deviating from previous findings of N-body simulations (e.g., Hahn et al. 2007b; Wang et al. 2011).

Initially, it is crucial to acknowledge that halo spin is closely linked to galaxy mass. Therefore, if the galaxy masses differ between subsamples, λ_h may also exhibit discrepancies. However, as depicted in panels (a) and (b) of Figure 2, the stellar masses and rotation velocities (representing halo mass; Mo et al. 1998) of the two subsamples are notably similar. This similarity is evidenced by the high p-values from K-S tests and the comparable median values of the distributions. Consequently, the observed spin variation with respect to environment cannot be solely attributed to differences in stellar mass or halo mass between the subsamples.

Second, it is important to recognize that certain H I-bearing galaxies may be characterized by a dominance of velocity dispersion over regular rotation. These galaxies, identified by their H I line profiles exhibiting a "single-horned" shape (ElBadry et al. 2018), pose challenges in accurately estimating rotation velocities and, consequently, halo spins. To distinguish between single-horned and double-horned H I spectra, we employ the kurtosis parameter k_4, following the methodology outlined in Hua et al. (2024). A spectrum is typically classified as single-horned if $k_4 > -1.0$.

Within our sample, approximately 12% exhibit single-horned H I line profiles with $k_4 > -1.0$. We focus on the robust subsets of isolated galaxies with double-horned H I profiles, excluding potentially dispersion-dominated galaxies. The results, as depicted in panel (b) of Figure 3, align with those of the complete data set.

Furthermore, it is worth noting the presence of small misalignments Δi between optical and H I inclinations observed in numerous galaxies (Hunter et al. 2012; Oh et al. 2015) and simulations (Nelson et al. 2018, 2019; Vogelsberger et al. 2019). However, the majority (70%) of galaxies exhibit $\Delta i < 20°$. In statistical terms, this misalignment would primarily increase the scatter within the spin distribution of each galaxy subsample, rather than bias the spin estimation (e.g., elevating or reducing spins across the entire sample). Hence, the observed spin variation with respect to environment cannot be attributed to potential inclination misalignments.

Finally, given the inclusion of numerous low-mass galaxies in our sample, where Equation (1) may not be directly applicable (Yang et al. 2023), we investigate the halo spin dependence for massive galaxies with stellar masses M_* $> 10^{9\cdot 5}$ M_ , as depicted in panel (c) of Figure 3. The results are consistent with those of the overall sample.

4. Summary

Utilizing the semi-analytic approach, we calculate the halo spins for a substantial sample of H I-bearing galaxies observed in ALFALFA. Our statistical analysis reveals a correlation between halo spin and environment, demonstrating that galaxies in denser environments tend to have lower halo spins on average. This trend could be linked to environmental gas stripping, potentially causing an underestimation of H I masses and consequent halo spins in non-isolated galaxies. Alternatively, baryonic processes may significantly modify the initial dark matter halo spins, deviating from previous results of N-body simulations. Further exploration with spatially resolved data is warranted.

Acknowledgments

Y.R. acknowledges support from the CAS Pioneer Hundred Talents Program (Category B), the National Natural Science Foundation of China (NSFC, grant No. 12273037), and the USTC Research Funds of the Double First-Class Initiative.

References

Alam, M. P., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12

Amorisco, N. C., & Loeb, A. 2016, MNRAS, 459, L51

Benavides, J. A., Sales, L. V., Abadi, M. G., et al. 2023, MNRAS, 522, 1033

Disney, M. J. 1976, Natur, 263, 573

Duc, P.-A., & Bournaud, F. 2008, ApJ, 673, 787

Durbala, A., Finn, R. A., Crone Odekon, M., et al. 2020, AJ, 160, 271

ElBadry, K., Quataert, E., Wetzel, A., et al. 2018, MNRAS, 473, 1930

Gardner, J. P. 2001, ApJ, 557, 616

Gault, L., Leisman, L., Adams, E. A. K., et al. 2021, AJ, 909, 19

Giovanelli, R., Haynes, M. P., Herter, T., et al. 1997, AJ, 113, 22

Giovanelli, R., Haynes, M. P., Kent, B. R., et al. 2005, AJ, 130, 2598

Hahn, O., Carollo, C. M., Porciani, C., & Dekel, A. 2007a, MNRAS, 381, 41

Hahn, O., Porciani, C., Carollo, C. M., & Dekel, A. 2007b, MNRAS, 375, 489

Haynes, M. P., Giovanelli, R., Kent, B. R., et al. 2018, ApJ, 861, 49

Hernandez, X., Park, C., Cervantes-Sodi, B., & Choi, Y.-Y. 2007, MNRAS, 375, 163

Hetznecker, H., & Burkert, A. 2006, MNRAS, 370, 1905

Hua, Z., Rong, Y., & Hu, H.-J. 2024, MNRAS, 538, 775

Huchra, J. P., Macri, L. M., Masters, K. L., et al. 2012, ApJS, 199, 26

Hunter, D. A., Ficut-Vicas, D., Ashley, T., et al. 2012, AJ, 144, 134

Janowiecki, S., Leisman, L., Józsa, G., et al. 2015, ApJ, 801, 96

Kim, J.-h., & Lee, J. 2013, MNRAS, 432, 1701

Li, X., Shi, Y., Zhang, Z.-Y., et al. 2022, MNRAS, 516, 4220

Liao, S., Gao, L., Frenk, C. S., et al. 2019, MNRAS, 490, 5182

Libeskind, N. I., Hoffman, Y., Steinmetz, M., et al. 2013, ApJL, 766L, 15

Maller, A. H., Dekel, A., & Somerville, R. 2002, MNRAS, 329, 423

Mo, H. J., Mao, S. D., & White, S. D. M. 1998, MNRAS, 295, 319

Nelson, D., Pillepich, A., Springel, V., et al. 2018, MNRAS, 475, 624

Nelson, D., Springel, V., Pillepich, A., et al. 2019, CompAC, 6, 2

Oh, S.-H., Hunter, D. A., Brinks, E., et al. 2015, AJ, 149, 180

Peebles, P. J. E. 1969, ApJ, 155, 393

Román, J., Jones, M. G., Montes, M., et al. 2021, A&A, 649L, 14

Rong, Y., Guo, Q., Gao, L., et al. 2017, MNRAS, 470, 4231

Rong, Y., Li, H., Wang, J., et al. 2018, MNRAS, 477, 230

Rong, Y., Hu, H., He, M., et al. 2024a, arXiv:2404.00555

Rong, Y., He, M., Hu, H., Zhang, H.-X., & Wang, H.-Y. 2024b, arXiv:2409.

Saulder, C., van Kampen, E., Chilingarian, I. V., Mikske, S., & Zeilinger, W. W. 2016, A&A, 596, A14

Tully, R. B., Rizzi, L., Shaya, E. J., et al. 2009, AJ, 138, 323

Vitvitska, M., Klypin, A. A., Kravtsov, A. V., et al. 2002, ApJ, 581, 799

Vogelsberger, M., Springel, V., Pillepich, A., et al. 2019, ComAC, 6, 2

Wang, H., Mo, H. J., Jing, Y. P., Yang, X., & Wang, Y. 2011, MNRAS, 413, 1973

Wang, J., Koribalski, B. S., Serra, P., et al. 2016, MNRAS, 460, 2143

Wang, B., Cappellari, M., Peng, Y., & Graham, M. 2020, MNRAS, 495, 1958

Wang, P., & Kang, X. 2017, MNRAS, 468L, 123

Wang, P., & Kang, X. 2018, MNRAS, 473, 1562

White, S. D. M. 1984, ApJ, 286, 38

Yang, H., Gao, L., Frenk, C. S., et al. MNRAS, 518, 5253

Zhang, C.-P., Zhu, M., Jiang, P., et al. 2024, SCPMA, 67, 219511

Note: Figure translations are in progress. See original paper for figures.