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The GECKOS Survey: Turning galaxy evolution on its side with highly resolved stellar population measurements of edge-on galaxies

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Abstract

GECKOS is a new survey targeting 35 edge-on disk galaxies with an ESO VLT/MUSE large program of 317 hours. GECKOS aims at unveiling the key physical processes of disk formation in nearby galaxies. Edge-on galaxies are ideal for this task: they allow us to disentangle the assembly history imprinted in the vertical structure of thin and thick disks and provide the greatest insights into gas outflows. The GECKOS sample was designed to trace properties of galaxies across a large range of star formation rates, bulge-to-total ratios, and boxy and non-boxy bulges. GECKOS is delivering spatially resolved measurements, at a spatial resolution better than 200 pc out to solar environments, of stellar abundances, ages, and kinematics, as well as ionized gas metallicities, ionization parameters and inflow and outflow kinematics. These are all key parameters for building a complete chemo-dynamical picture of disk galaxies. After introducing the survey, I focus here on the study of the stellar populations and origin of thick disks in the GECKOS sample. I present the first results for 6 galaxies, which have a clear thick and thin disk structure, observed during the survey's first semester. I show maps of stellar ages, metallicity and [Mg/Fe] abundance and investigate trends of thick disk properties with the galaxy star formation rate (SFR). Galaxies with different star-formation rates show different properties, indicating different evolutionary paths. Galaxies above the star-formation main sequence do not show sharp differences between thick and thin disks. The former are relatively young, while older than their thin disks. On the other hand, galaxies around the main sequence and slightly below clearly display an old, metal-poor and α-enhanced thick disk, and a young, metal-rich thin disk.

1 Introduction

The chemo-dynamic history of spiral galaxies results from a complex interplay of internal and external processes, whose combination leads to a wealth of structures that vary from galaxy to galaxy. Thus, reconstructing the complete galaxy evolution is challenging, leaving many open questions. The vertical and radial distributions of properties of stars and gas bring the footprint of the galaxy evolution history, and the latter can be reconstructed using deep observations of edge-on galaxies. These help disentangle intriguing stellar components such as thin and thick disks, whose properties vary between galaxies and whose origin remains unclear. Key questions include the formation of thick disks, how and when galaxies transition from thick- to thin-disk formation, the evolutionary connection between them, and the role of galaxy mergers in shaping them.

Thick disks have been traditionally found to be much older and metal poor than the thin disks, both in the Milky Way and in early-type disk galaxies [9, 20, 12, 13, 11]. Different formation scenarios were proposed to explain these properties and the later transition to thin disk formation. One possibility is in situ formation at high redshift, from dynamically hot gas, during the epoch of gas-rich mergers [3]. Only later in time, the gas cooled down and lead to the formation of the thin disk. A second possibility is that thick disk stars formed in a thinner disk, and only later were dynamically heated and acquired higher velocity dispersions [15, 8]. On the other hand, thin disk stars had not had time yet to be dynamically heated. A third alternative would be a thick disk mostly made up by accreted stars, while the thin disk would be assembled later on in a quiescent phase [1].

Spatially resolved stellar population studies of edge-on disk galaxies, using high-spatial-resolution integral-field spectroscopy (IFS) data from the Multi Unit Spectroscopic Explorer (MUSE) at the Very Large Telescope (VLT), showed that a combination of more than one of these formation scenarios are necessary to explain the star-formation histories and metallicity distributions of thick disks [12, 13, 11]. This complex picture, with the essential combination of in-situ formation at high redshift and later accretion of stars from satellites, was reaffirmed by cosmological simulations of Milky Way-mass galaxies [14]. However, these also revealed that some thick disks are younger, mostly due to recent mergers providing large amounts of gas to fuel later star formation, in addition to younger accreted stars.

The above mentioned observational studies focused on early-type more massive disk galaxies and found very old and metal-poor thick disks, with a sharp transition into young and metal-rich thin disks [12, 11]. A very recent study on stellar populations of gas-rich, star-forming, late-type spirals have unveiled a different picture: thick disks are not necessarily old and they were not entirely assembled at early times in all galaxies. In these globally young and metal-poor galaxies, they are in fact relatively young, and do not show a large difference with the slightly younger and less metal-poor thin disk [16]. In this work, we aim to expand the analysis to a larger sample, and investigate trends with galaxy properties such as star-formation rates (SFRs).

2 The GECKOS Survey and the sample

GECKOS (Generalising Edge-on galaxies and their Chemical bimodalities, Kinematics, and Outflows out to Solar environments[1], PIs: Jesse van de Sande and Amelia Fraser-McKelvie) is a new VLT/MUSE survey with 317 allocated hours of observations. It targets 35 edge-on Milky Way-mass disk galaxies, with high spatial resolution (< 200 pc) out to solar radii and reaching a signal-to-noise ratio of at least 40 Å^{-1} per spatial bin out to a surface brightness of 23.5 mag arcsec^{-2} [19]. This is allowing to spatially resolve stellar population and kinematic properties in the galaxy disk, as well as ionized gas properties such as inflow and outflow kinematics. The main goal of the survey is to unveil the key

[1] http://geckos-survey.org/

physical processes that drive the mass assembly and evolution of disk galaxies.

The sample includes edge-on galaxies (with inclinations above 85º) with a stellar mass similar to the Milky Way (within ±0.3 dex) and closer than 70 Mpc from us. These galaxies were selected across a large range of SFRs, distributed above, below and within the star formation main sequence region, allowing a large range of morphologies across the Hubble sequence. While the sample was limited to a bulge-to-total ratio below 0.5, it includes a similar number of galaxies with and without box/peanut bulges. The analysis presented here was performed when the first eleven galaxies of the survey were fully reduced and included in the first internal data release. In this work, I present the stellar populations of the six galaxies that have a clear morphological thick and thin disk structure, among these first eleven galaxies, according to [7]. Relevant properties of the galaxies are indicated in Table 1. More details about the survey and the sample will be presented in van de Sande et al. (in prep.).

Table 1: Relevant properties of the six galaxies in our sample.

Galaxy name	M_* (10^{10}M$_\odot$) [a]	SFR (M$_\odot$/yr) [b]	z_{tT} (arcsec) [c]
IC 1711	4.0	1.1	6.5
ESO 079-003	3.9	6.1	5.8
NGC 0522	4.8	0.6	5.9
NGC 3279	3.2	2.0	3.9
NGC 3957	3.3	0.3	14.2
UGC00903	3.8	4.2	8.4

[a] Stellar mass, from the S4G Survey [17]

[b] Star formation rates determined from Wise W4 photometry following [6]

[c] distance from the midplane beyond which the thick disk starts to dominate over the thin disk, according to the morphological decomposition from [7].

3 Method

The GECKOS data analysis team has developed nGIST (Fraser-McKelvie et al., in prep.), a new updated version of the GIST pipeline [2]. This is a modular pipeline dedicated to the analysis of IFS data cubes. We used this pipeline to obtain the results presented here. The modules that were used for this work include: the Preparation Module, including some spatial masking of bad pixels and foreground or background objects, the Voronoi binning [4], the Stellar Kinematics and the Star Formation History Modules, both using the Penalized Pixel Fitting (pPXF) method [5]. We used a wavelength range between 4800 and 7000Å. A target signal-to-noise ratio (S/N) of 100 Å^{-1} was used for the Voronoi binning, while filtering all spaxels with a S/N < 1.5. The stellar kinematics was fitted using the Indo-US Stellar Library [18] and an additive polynomial of degree 12. The stellar populations were obtained using the sMILES simple stellar population (SSP) models [10], with variable [Mg/Fe] abundances. Emission lines were masked and the stellar kinematic parameters were kept fixed to the results from the corresponding module of the pipeline. A multiplicative polynomial of degree 12 and a regularization parameter of 2 were used.

4 Results

We show in Fig. 1 the stellar population maps of the six galaxies in the GECKOS subsample presented here. From left to right, galaxies are ordered with increasing SFR, and from top to bottom we show the average age, total metallicity [M/H] and [Mg/Fe] abundance of each spatial bin. To analyze the stellar population properties of the thick and the thin disks we used a geometric definition of them, based of the morphological decomposition from [7]. The region between the two white dashed horizontal lines defines the geometric thin disk (its light dominates in this region), while the thick disk is defined by the regions below and above the thin-disk dominated region, where it dominates over the thin disk.

In all galaxies, the midplane region displays younger ages and higher metallicities. However, average ages decrease from the left to the right in Fig. 1, in particular in the thick disk. Global metallicities, but especially metallicities in the thin disks, are higher in galaxies on the left side of the figure, with a lower SFR. [Mg/Fe], finally, have sharper differences between thick and thin disks in the galaxies on the left side (lower SFR), with more pronounced [Mg/Fe] enhancement in their thick disks. In general, stellar population maps of galaxies on the left side are more similar to previously analyzed earlier-type disk galaxies [12, 13, 11], with old, metal-poor and [Mg/Fe]-enhanced thick disks showing a sharp transition to the thin disk. On the other hand, galaxies on the right side have much in common with a recently published sample of very late-type galaxies [16], with relatively young thick disks with recent star formation, and small differences with the thin disks.

We have investigated more in details trends of the thick disk stellar population properties with galaxy SFRs, as showed in Fig. 2. Thick disk ages and [Mg/Fe] abundances show a clear trend with SFRs. More quiescent galaxies have a very old thick disk (with ages of about 10-12 Gyr) and star-forming galaxies have a relatively young thick disk (with intermediate ages, between 4 and 8 Gyr). Metallicity of thick disks does not show a trend with the galaxy SFR, with all average [M/H] values below -0.3 dex. Finally, old thick disks in quiescent galaxies are clearly enhanced in α elements (represented here by magnesium), with [Mg/Fe] abundances between 0.2 and 0.4 dex, while [Mg/Fe] is closer to solar values (but still larger than 0.1 dex) in the youngest thick disks of star-forming galaxies.

Our results suggest that galaxies that are now more quiescent had a faster evolution and formed their thick disks at early times and in a fast time scale. On the other hand, the mass assembly of galaxies that are still intensively forming stars has been much slower, and the formation of their thick disks has been extended until recent times.

5 Summary, conclusions and future steps

We have presented here the first results of stellar populations of thick disks in the GECKOS survey, a new deep survey of edge-on galaxies observed with MUSE/VLT. For this purpose, we analyzed six edge-on galaxies of the first fully reduced sample of eleven galaxies, which have a clear morphological

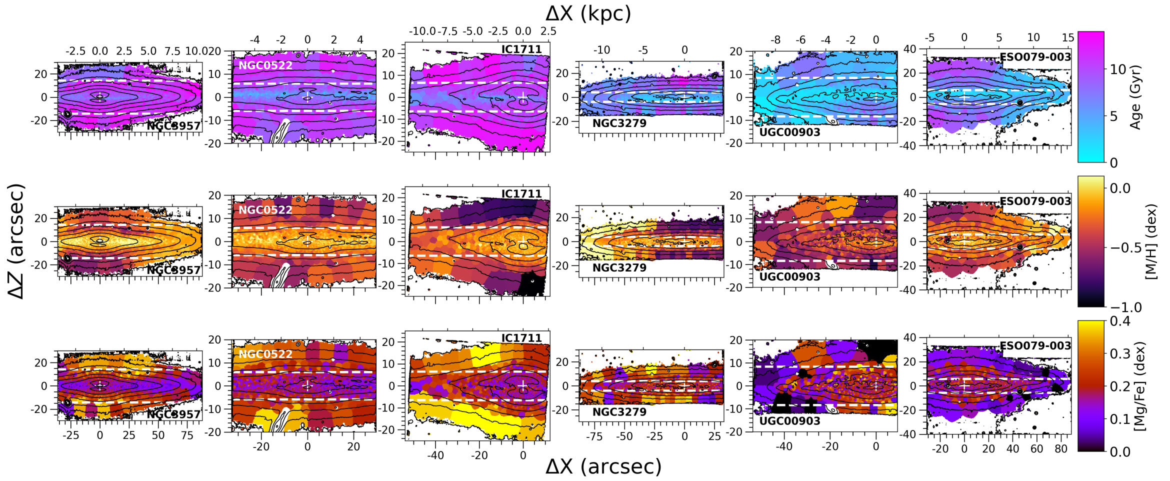

Figure 1: Stellar population maps of the six galaxies in our sample. From top to bottom, age, total metallicity [M/H] and [Mg/Fe] abundance. From left to right, galaxies with increasing star formation rate, whose names are indicated in each panel (NGC 3957, NGC 0522, IC 1711, NGC 3279, UGC 00903, ESO 079-003). White dashed horizontal lines indicate the distance z_{tT} from the midplane beyond which the thick disk starts to dominate over the thin disk.

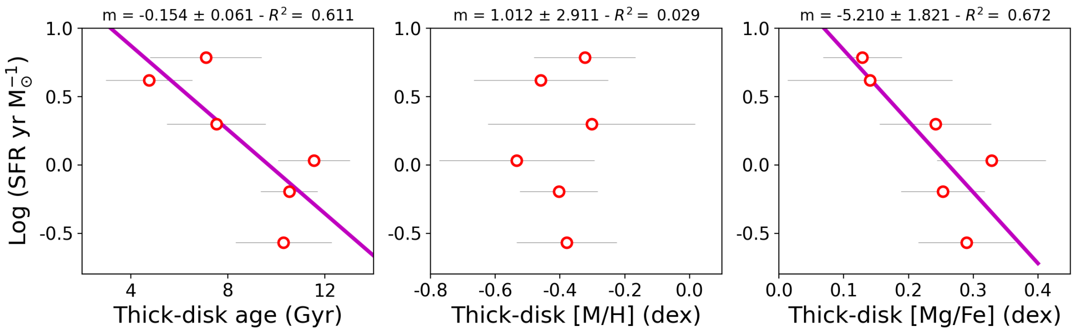

Figure 2: Trends of the stellar population properties of the six thick disks in our sample with the galaxy SFRs. From left to right: age, [M/H] and [Mg/Fe]. Each point corresponds to one galaxy, and a linear regression is shown in magenta when there is a clear correlation. Above each panel, we indicate the slope of the linear regression and the correlation coefficient R^2. Error bars indicate the standard deviation of the distribution of the represented property in different Voronoi bins.

distinction between thin and thick disks. These six galaxies have different SFRs and the stellar population properties of their thick and thin disks show trends with their SFRs. In general, more quiescent galaxies have a sharp distinction between the very old, metal-poor and [Mg/Fe]-enhanced thick disks and the younger, metal-rich thin disks. This distinction becomes less clear in strongly star-forming galaxies, which are in general more metal poor and have thick disks that are relatively young and less enhanced in [Mg/Fe]. This suggests a fast formation at high redshift for thick disks in more quiescent galaxies, with a later slower formation of thin disks. Strongly star forming galaxies, on the other hand, might have had a slower evolution at early times, and a more extended formation of (their relatively young) thick disks, with no clearly sequential distinction between the formation time of thick and thin disks.

We are currently testing different parameters such as regularization, spectral ranges for the fits, and different set ups in general, with the goal of fine tuning the final configuration and extract the star-formation histories of thick and thin disks and reconstruct their mass assembly. We are calculating random uncertainties of the stellar population properties with Monte Carlo simulations. All the final results will be included in a paper in preparation (Pinna et al., in prep.).

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References

[1] Abadi, M. G., Navarro, J. F., Steinmetz, M., & Eke, V. R. 2003, ApJ, 597, 21

[2] Bittner, A., Falcón-Barroso, J., Nedelchev, B., et al. 2019, A&A, 628, A117

[3] Brook, C. B., Kawata, D., Gibson, B. K., & Freeman, K. C. 2004, ApJ, 612, 894

[4] Cappellari, M. & Copin, Y. 2003, MNRAS, 342, 345

[5] Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138

[6] Cluver, M. E., Jarrett, T. H., Dale, D. A., et al. 2017, ApJ, 850, 68

[7] Comerón, S., Salo, H., & Knapen, J. H. 2018, A&A, 610, A5

[8] Di Matteo, P., Lehnert, M. D., Qu, Y., & van Driel, W. 2011, A&A, 525, L3

[9] Gilmore, G., & Reid, N. 1983, MNRAS, 202, 1025

[10] Knowles, A. T., Sansom, A. E., Vazdekis, A., & Allende Prieto, C. 2023, MNRAS, 523, 3450

[11] Martig, M., Pinna, F., Falcón-Barroso, J., et al. 2021, MNRAS, 508, 2458

[12] Pinna, F., Falcón-Barroso, J., Martig, M., et al. 2019a, A&A, 625, A95

[13] Pinna, F., Falcón-Barroso, J., Martig, M., et al. 2019b, A&A, 623, A19

[14] Pinna, F., Walo-Martín, D., Grand, R. J. J., et al. 2024, A&A, 683, A236

[15] Quinn, P. J., Hernquist, L., & Fullagar, D. P. 1993, ApJ, 403, 74

[16] Sattler, N., Pinna, F., Comerón, S., et al. 2024, , arXiv e-prints, arXiv:2410.05761

[17] Sheth, K., Regan, M., Hinz, J. L., et al. 2010, PASP, 122, 1397

[18] Valdes, F., Gupta, R., Rose, J. A., et al. 2004, ApJS, 152, 251

[19] van de Sande, J., Fraser-McKelvie, A., Fisher, D. B., et al. 2023, arXiv e-prints, arXiv:2306.00059

[20] Yoachim, P., & Dalcanton, J. J. 2008a, ApJ, 683, 707