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Chemo-dynamic clues to the birthplaces of exoplanetary systems

Juan José García-Delgado[1], M. L. L. Dantas[2], I. Rebollido[3], R. Smiljanic[4]

[1]Space Research Group, Universidad de Alcalá, 28805 Alcalá de Henares, Spain
[2]Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
[3] Centro de Astrobiología (CAB) CSIC-INTA, Camino Viejo del Castillo s/n, E-28692, Villanueva de la Cañada, Madrid, Spain
[4] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716, Warsaw, Poland

Abstract. As stars orbit the Galaxy, their trajectories are perturbed by gravitational interactions with the Milky Way's major structures, such as the bar and spiral arms. Although the dynamical influence of these structures on stellar motion is relatively well understood, their effects on planetary systems remain unexplored. We present a homogeneous sample of stars hosting confirmed exoplanets, built by crossmatching the Encyclopaedia of Exoplanetary Systems with *Gaia* DR3. Distances were estimated using a Bayesian approach, orbits were integrated over 10 Gyr, and birth radii were inferred from Galactic chemical evolution models combined with a generalised additive model. Preliminary results indicate that most stars in our sample belong to the thin disc and seem to have predominantly migrated outward from their birthplaces, with a minority showing inward relocation. Systems are further categorised by the types of planets they host, highlighting possible correlations between stellar motion and planetary system architecture, and combined companions mass. These results suggest that Galactic chrono-chemo-dynamics may help identify environments where habitable worlds, and potentially technosignatures, are more likely to arise.

Keywords. Exoplanets, planetary systems, Galactic chemo-dynamics, radial migration, stellar birth radii, Milky Way Galaxy, habitability, technosignatures

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1. Introduction

Over Galactic timescales, stellar orbits can be reshaped by radial migration and dynamical heating (Sellwood 2014), so that stars in the solar neighbourhood today may have formed far from their current locations. This redistribution, commonly referred to as radial mixing (Sellwood & Binney 2002), means that the local population of planet-hosting stars is not chemo-dynamically homogeneous; it contains systems formed in different environments throughout the Milky Way.

This Galactic context could be relevant for understanding why planetary systems display such diverse architectures. Planet formation is closely linked to the properties of the host star (Teske 2024) and its birth environment (Nielsen et al. 2023), while the long-term survival of planets may also depend on the dynamical history experienced by the entire star-planets system. A chrono-chemo-dynamical perspective therefore provides a complementary way to interpret exoplanet demographics, connecting present-day planetary architectures with the formation environments and orbital histories of their host stars.

This contribution summarises a preliminary chrono-chemo-dynamical exploration of confirmed exoplanet host stars, which will be developed further in a forthcoming publication. We investigate their motion histories by comparing inferred birth radii ($\langle R_{\rm b}\rangle$†) with present-day guiding radii ($\langle R_{\rm g}\rangle$), and analyse whether different migration (or lack thereof) features (e.g.

† We adopt median values due to our bootstrap technique.

migration direction or length) are associated with differences in planetary companions and orbital architectures. In this way, Galactic chrono-chemo-dynamics may provide a useful context for Galactic habitable zone (GHZ; e.g. Stojković, N. 2019) studies and help prioritise life-friendly environments in future technosignature searches.

2. Sample and methods

We analysed a sample of $\sim$ 1400 planet-hosting stars currently in the solar neighbourhood, selected from the *Encyclopaedia of Exoplanetary Systems* (Schneider et al. 2011) and cross-matched with *Gaia* DR3 (Gaia Collaboration et al. 2023). We focus on thin disc systems, since Galactic chemical evolution models depict clearer metallicity gradients for the thin disc. The sample used here have been filtered according to the astrometric-quality criteria recommended by Fabricius et al. (2021, Sect. 3.3).

For each host star, Galactic orbits were integrated over a 10 Gyr lookback time using GALPY (Bovy 2015), adopting the Milky Way Galactic potential from McMillan (2017). We then estimated the present-day $\langle R_{\rm g} \rangle$ together with other dynamical parameters, such as orbital eccentricities, velocities, and action; $\langle R_{\rm b} \rangle$ were inferred following Dantas et al. (2025) from a generalised additive model (GAM) extension of the Galactic chemical enrichment models from Magrini et al. (2009). By comparing $\langle R_{\rm g} \rangle$ with $\langle R_{\rm b} \rangle$, we defined the radial displacement as $\Delta R = R_{\rm g} - R_{\rm b}$ and classified host stars as outward, non-, or inward migrators. We also grouped systems according to their companions, based on their mass and radius, and analysed the outermost semi-major axis of a detected companion ($a_{\max}$) in each system as a simple tracer of orbital architecture.

3. Results and discussion

In the left panel of Fig. 1 we compare the distributions of $\langle R_{\rm g} \rangle$ and $\langle R_{\rm b} \rangle$ for host stars grouped by planetary content, distinguishing between systems hosting only rocky or giant planets, brown dwarf (BD) companions, or combinations of these. In the right panel we consider $a_{\max}$ in each system as a simple proxy for the radial extent or compactness of the planetary architecture.

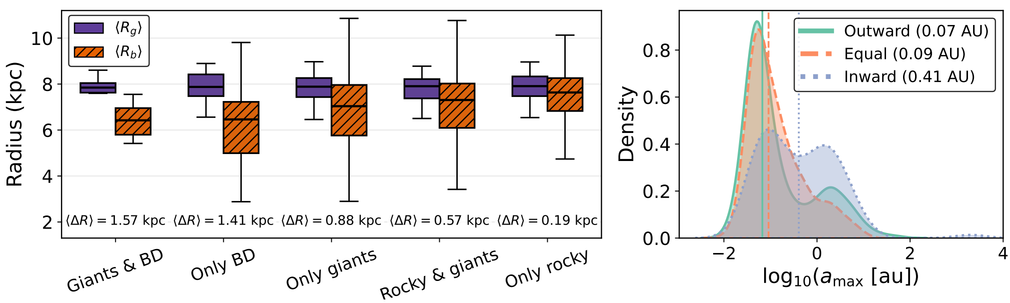

Figure 1. Left: boxplots of $\langle R_{\rm g} \rangle$ and $\langle R_{\rm b} \rangle$ for planetary systems grouped by planet-type category. Right: Gaussian kernel density distributions of $a_{\max}$, for the distinct motion classes: outward, non- and inward migrators. Vertical lines indicate median values.

Systems hosting more massive companions (giant planets and BDs) tend to show larger ΔR, being preferentially formed at smaller Galactocentric radii. These results are consistent with the metallicity dependence of giant-planet formation, given that the Galactic disc exhibits a negative radial metallicity gradient and its innermost regions experienced rapid chemical enrichment (Magrini et al. 2023; Molero et al. 2024). In contrast, rocky-only systems show smaller collective ΔR, originate at generally larger $R_{\rm b}$, and exhibit one of the narrowest $R_{\rm b}$

distributions, possibly pointing to a preferred formation region. No clear correlation is found between ΔR and planetary multiplicity.

Outward migrators tend to host more compact systems, while their inward moving counterparts show a broader distribution extending to larger planetary orbits, with the non-migrator distribution more closely resembling that of outward migrators. This may suggest that the dynamical histories associated with outward migration preferentially affect planets on wider orbits. However, this interpretation must be considered with caution, since detected planetary systems are affected by observational biases and heterogeneous detection methods.

From the perspective of technosignature searches, rocky planets may be considered a basic requirement for potentially habitable worlds. Figure 1 suggests that systems hosting rocky planets tend to originate at larger Galactocentric distances and show smaller radial displacements than giant-planet and BD hosts. This points to a possible chemo-dynamical criterion for identifying stellar candidates for future habitability studies.

4. Conclusions

This contribution presents a preliminary chrono-chemo-dynamical view of planet-hosting stars in the solar neighbourhood. Our results suggest that the radial migration history is connected to the planetary content, with those hosting more massive systems being formed at smaller Galactocentric distances and, therefore, showing larger radial displacements. This result is in alignment with previous works that show the relationship between metallicity and giant-planet occurrence, since the Galactic inner regions are progressively more metal-rich. We also find tentative differences in the outermost detected semi-major axes across the direction of migration classes, with outward migrators appearing more compact than inward migrators. Although these trends must be interpreted with caution, considering observational biases such as heterogeneous detection methods, survey selection effects, and sample heterogeneity, they support the idea that the Galactic birth environment and dynamical evolution may provide useful context for understanding planetary system architectures. While more detailed work is required, Galactic chemo-dynamics could be considered when identifying regions of interest for future habitability and technosignature studies. The upcoming *Gaia* DR4, together with the expected PLATO exoplanet yield, will enlarge the parameter space for this type of study.

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