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Interstellar Objects in the Context of the Milky Way's Thin and Thick Disks

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ABSTRACT

The division of the Milky Way's disk into "thin" and "thick" components is a common practice, but one that is often ambiguously defined. The two ways of dividing stars are not equivalent: many stars belonging to the stellar population at high [α/Fe] (the "chemical thick disk") do not belong to the larger-scale-height exponential density component of Gilmore & Reid (1983) (the "kinematic thick disk"). Furthermore, the existence of two distinct kinematic components is debated (Bovy et al. 2012). This issue has surfaced in discussions about the recently discovered interstellar object 3I/ATLAS, which likely originated around an old star (Hopkins et al. 2025b; Taylor & Seligman 2025), and has been variously classified as a member of both the "thin disk" and the "thick disk" by different works. We illustrate that the origins of interstellar objects should be discussed with care, and relative to specific, identified populations of stars.

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1. THESE AREN'T THE DISKS YOU'RE LOOKING FOR

Gilmore & Reid (1983) found that the spatial distribution of stars far from the Galactic plane was well fit by a double exponential density model with two scale heights: one $\approx 300\,\mathrm{pc}$ and the other $\approx 1450\,\mathrm{pc}$. They termed these two exponential components the "thin" and "thick" disks respectively. Under the assumption that these two components of the density model corresponded to two distinct stellar populations, some works assigned stars nearer the Galactic midplane to each based on their velocities (e.g. Bensby et al. 2003). This is the first way of dividing the Milky Way's stars into two disks: **kinematics**.

Separately, as spectral elemental abundance measurements improved, two truly distinct stellar populations were discovered in the [Fe/H]–[α/Fe] distribution (Tinsley 1979), illustrated here in Fig. 1 with [Mg/Fe] tracing the abundance of α elements. One population has approximately Solar abundances of [α/Fe] ≈ 0 and [Fe/H] ≈ 0, and the other has enhanced values of [α/Fe] with lower average metallicity. Since it was known that the stars assigned to the "kinematic thick disk" had a lower average metallicity than stars assigned to the "kinematic thin disk" (Gilmore & Wyse 1985), it was assumed that the two truly distinct populations in [α/Fe] corresponded to the two components of the density model used by Gilmore & Reid (1983), with the kinematic thin and thick disks equated with the low- and high-α populations respectively (the first appearance in the literature is Fuhrmann 1998). The high-α population of stars began to be referred to as "the thick disk" in entirely non-kinematic studies (e.g. Masseron & Gilmore 2015). This is the second way of dividing the Milky Way's stars: **chemistry**.

These two ways of dividing the Milky Way's stellar population into thin and thick disks are not equivalent: many "chemical thin disk" stars have "kinematic thick disk" orbits and *vice versa* (Fig. 1, and Hayden et al. 2017; Bland-Hawthorn et al. 2019). Furthermore, in reality the Milky Way has no distinct "kinematic thick disk" at all (Bovy et al. 2012): the stellar population is better fit by a continuum of spatial scale heights, which vary smoothly with chemical abundances and age (Bovy et al. 2016; Mackereth et al. 2017). The low- and high-α populations, though distinct in chemistry, are not distinct in other properties (Hayden et al. 2017, 2020) and strongly overlap in kinematics.

In the field of interstellar objects (ISOs), various works have attempted to classify the recently-discovered

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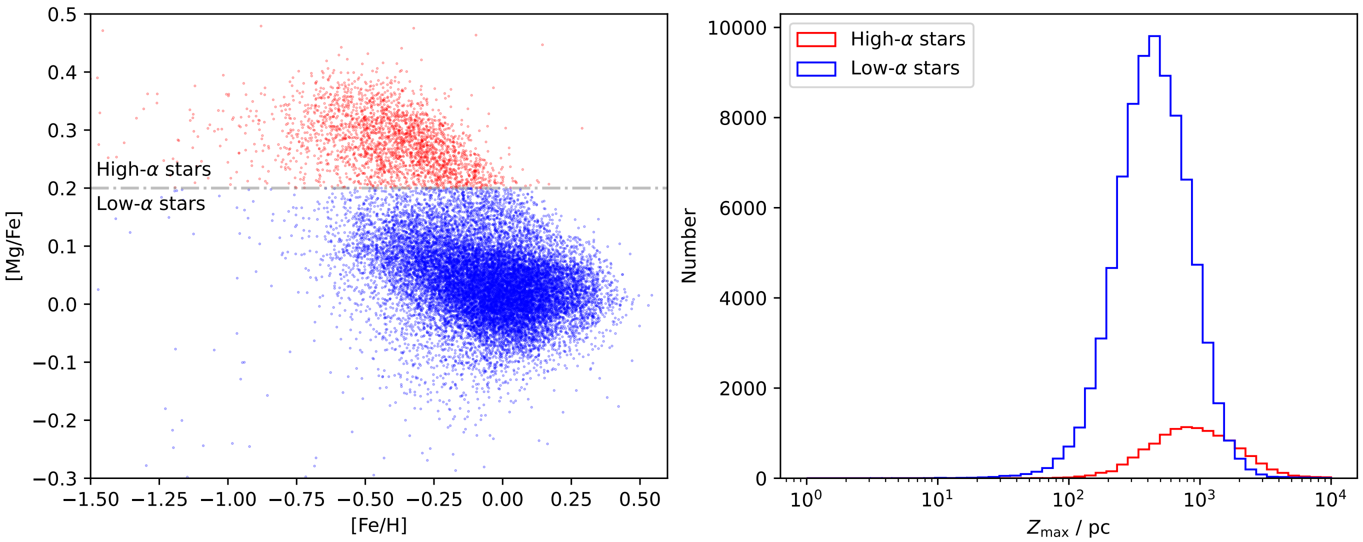

Figure 1. A sample of 93203 stars from APOGEE DR17 (Abdurro'uf et al. 2022), cut to a cylindrical Solar neighbourhood of radius 500 pc with $T_{\rm eff} \geq 4500\,{\rm K}$ and EXTRATARG = 0 for well-measured abundances (Jönsson et al. 2020). Survey selection biases have not been accounted for. Though there are two distinct populations in chemistry (left), these are not distinct in kinematics, illustrated with their distributions in $Z_{\rm max}$ (right), the maximum vertical height of each star's Galactic orbit. *Thus, most ISOs cannot be confidently assigned to either chemical population based on kinematics alone.*

3I/ATLAS as originating in either the "thin disk" or "thick disk", without specifying if they are using chemical or kinematic definitions. This has led to ambiguity and contradicting classifications (e.g. de la Fuente Marcos et al. 2025; Eubanks et al. 2025; Guo et al. 2025; Cordiner et al. 2026).

2. WHAT DOES THIS MEAN FOR ISOS?

Though the Milky Way's stellar population cannot be divided into distinct kinematic thin and thin disks, there are still correlations between velocity, age and elemental abundances, and these can be used to infer confidence intervals on the properties of the origin stars of ISOs. For example, shortly after the discovery of 3I/ATLAS Hopkins et al. (2025b) and Taylor & Seligman (2025) concluded that its velocity indicated an origin around an older, lower-metallicity, higher-α star than those of the two previously discovered ISOs.

In an early pre-print version of the Hopkins et al. (2025b) manuscript, posted on arXiv 86 hours after the discovery of 3I/ATLAS, we claimed its high vertical motion implied an origin in "the Milky Way's thick disk" without either clarifying which of the kinematic or chemical definitions we meant, or quantitively testing this. We quickly regretted this, and removed the ambiguous claim in the published version.[3]

To deduce the origin population of an ISO using its velocity alone, the following must be considered. Since the terms "thin disk" and "thick disk" have multiple definitions in the literature, it is important to be clear which properties are being used to divide stars: kinematics, or chemical abundances. Additionally, the only truly distinct populations are those separated by chemical abundances, and even these overlap in kinematics. The probability of a newly-discovered ISO being a member of each population could be calculated by measuring the velocity distributions of the low- and high-α stellar populations and comparing the likelihoods of the ISO's velocity being drawn from each, similar to the method of Guo et al. (2025). This however requires significant care: the stellar sample used must be restricted to the Solar neighbourhood, the velocity distribution of which is complex with local non-Gaussian structures (Hopkins et al. 2025a; Lucchini et al. 2023), and survey selection bias must be accounted for.

Fig. 1 shows that both low- and high-α stars are found at 3I's $Z_{\rm max} \sim 500\,{\rm pc}$ (calculated with *Galpy*; Bovy 2015), therefore strongly constraining 3I's origin population using just its velocity may not be possible. Cordiner et al. (2026) however suggest an origin for 3I/ATLAS in the high-α stellar population based on its measured coma $^{12}{\rm C}/^{13}{\rm C}$ ratio. Thus, when overlapping kinematics make determining an ISO's origin population difficult using velocity alone, a more effective alternative may be to measure its chemical composition directly.

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[3] The published paper thanks Eric Mamajek for the correction.

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