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INFERRING PLANETARY SYSTEM ARCHITECTURES FROM ORBITAL DATA AND DISK MORPHOLOGY

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Abstract. We present a three-step approach to studying the architecture and dynamics of planetary systems, combining observations, orbital fitting, and N-body dynamical modeling with our in-house codes `Oracle` and `Astroide`. High-contrast imaging, astrometry, and radial velocity data provide the basis, while Bayesian fitting and long-term integrations link planets, stars and disks. We illustrate this methodology with three emblematic systems: in GG Tauri, disk observations help discriminate among orbital-fit solutions of the central triple; in β Pictoris, the morphology of the debris disk indicates an additional planet interior to $\sim$50 AU; and in TWA7, the inner edge of the disk at $\sim$23 AU also suggests the presence of an additional planet, while possible trojans on the orbit of the recently detected planet constrain the eccentricities of the system's planets. These applications highlight how joint orbit-disk analysis can reveal unseen companions and refine orbital parameters.

Keywords: Orbital fitting; N-body simulations; Celestial mechanics; Debris disks; Individual Stars (GG Tauri, Beta Pictoris, TWA 7)

1 Introduction

Recent advances in high-contrast imaging (Lagrange et al. 2010; Keppler et al. 2018) and precision astrometry (Gaia Collaboration et al. 2021) now enable detailed orbital measurements of planets and stellar multiples. At the same time, debris disks are recognized as privileged tracers of dynamical evolution (Wyatt 2008; Hughes et al. 2018): disk morphologies trace gravitational imprints, constraining known bodies and revealing unseen ones. Our objective is to combine observational data with orbital fitting and dynamical simulations in order to reconstruct architectures and test evolutionary scenarios for several emblematic young systems. We focus in particular on those still hosting debris disks, as they are at evolutionary stages where planet-disk interactions remain directly observable.

2 Methodology

1) Observations. We use direct imaging, astrometry, and radial velocity data, providing the positions and motions of bodies as well as the morphology of disks.

2) Orbital fitting. With our `Oracle` code (`https://github.com/lacquema/Oracle`), based on Bayesian inference and MCMC exploration, we reconstruct the orbits of stars and planets, and estimate orbital parameters with associated uncertainties. A key feature is the ability to fit multiple orbits simultaneously, essential for complex planetary and stellar systems such as hierarchical multiples. The code also provides a user interface to guide users in launching and analyzing solutions, and allows selection of specific cases from the posterior distribution, which is particularly useful before testing them dynamically in the third step.

3) Dynamical modeling. The fitted orbits are integrated with our `Astroide` code (`https://github.com/lacquema/Astroide`), a symplectic N-body integrator that includes stars, planets, and the debris disk to explore

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long-term evolution and interactions. Two algorithms are available: RMVS3 (Levison & Duncan 1994) is designed for planetary systems dominated by a central star, and efficiently handles close encounters and planet-planetesimal scattering, and HJS, adapted to hierarchical multiple stellar systems and their long-term secular evolution (Beust 2003). The disk radial profile of the surface density is a key diagnostic, accessible through a user interface that also facilitates comparison across runs.

3 Applications

GG Tauri. This rare multiple stellar system, where five stars interact with a circumtriple disk, offers an exceptional case for testing orbital fitting. We obtain robust constraints on the masses and the architecture of the central triple. Only a subset of the fitted solutions reproduce the observed disk morphology, particularly the inner edge near 190 AU (Guilloteau et al. 1999; Dutrey et al. 2014), showing how disks discriminate among orbital configurations (Lacquement, in prep).

β **Pictoris.** Hosting two directly imaged giant planets and a well-observed debris disk, this system provides a benchmark for confronting models with observations. Using orbital parameters constrained from high-resolution observations (Lagrange et al. 2010; Lacour et al. 2021), our simulations show that the two known planets cannot explain the inner edge at $\sim$50 AU observed by Dent et al. (2014), suggesting the presence of an additional body interior (Lacquement et al. 2025).

TWA 7. A planet was recently detected (Lagrange et al. 2025). However, the disk edge at $\sim$23 AU observed by Ren et al. (2021) cannot be explained by this body alone, suggesting the presence of an additional companion, in analogy with β Pictoris. Moreover, possible trojan-like structures along the detected planet's orbit provide further constraints on the eccentricities of the system's planets (Lacquement, in prep).

4 Conclusions and perspectives

The morphology of debris disks offers insights into the architectures of host stars and planets. The three cases are complementary, each highlighting different aspects of our three-step methodology and together demonstrating its strength. With high-quality data, this framework can be applied broadly, and upcoming facilities such as Gaia DR4, JWST, and the ELT will extend it to larger samples, paving the way toward a statistical view of planetary systems. Beyond these examples, it is already applied to other young debris-disk hosts, and catalogs such as Pearce et al. (2022) offer promising targets.

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