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A six dimensional view of stellar and planetary systems with high precision astrometry

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Abstract

High-precision astrometry provides the six-dimensional information (position and velocity) of individual members in stellar systems. In this contribution, I present our work on using radio astrometry, complemented with *Gaia*, to study the 3D structure of star-forming regions and the internal kinematics of young stellar clusters. I also present recent wok on astrometric searches for exoplanets in single and binary stars and the characterization of their 3D orbits.

Resumen

Astrometría de alta precisión proporciona información sobre la posición y velocidad de miembros individuales en sistemas estelares. En esta contribución, presento nuestro trabajo sobre el uso de la radio astrometría, complementada con *Gaia*, para estudiar la estructura 3D de regiones de formación estelar y la cinemática interna de cúmulos estelares jóvenes. También presento trabajos recientes sobre búsquedas astrométricas de exoplanetas en estrellas aisladas y binarias, así como la caracterización 3D de sus órbitas.

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1. Introduction

Significant progress in astrometric accuracy was achieved in the last decade with the launch of the *Gaia* mission and the development of Radio Interferometry. In the field of star and planet formation, the unprecedented astrometric precision provided by these instruments opened new lines of research that were previously inaccessible. *Gaia* is collecting the parallax and proper motions of $>$ 1000 million stars, which represents $\sim$1% of the stars in the Galaxy. In the current Data Release 3 (DR3), uncertainties in parallax and proper motions are 10–20 μas and 10–20 μas yr^{-1}, respectively, both for a magnitude below $G = 15$ (Gaia Collaboration et al., 2023). For astrometric studies in star-forming regions, however, it is necessary to complement *Gaia* measurements with the astrometry provided by radio interferometers. This is because star formation occurs in molecular clouds, within dense cores rich in dust. Radio observations, on the other hand, can overcome the high dust extinction, allowing astrometric measurements of the youngest and most embedded objects.

2. 6D structure of molecular clouds and young stellar systems

We conducted the Gould's Belt Distances Survey (GOBELINS), a radio astrometric survey of (embedded) young stellar objects located in the most prominent and nearby star-forming regions (Taurus, Perseus, Serpens, Ophiuhcus and Orion). GOBELINS used the Very Long Baseline Array (VLBA) to observe the non-thermal radio continuum emission from $\sim$ 270 targets, delivering high precision astrometric parameters of about 100 stars. Published catalogs contain parallaxes and distances with an accuracy of 0.3% to a few percent, and proper motions accuracies better than 0.2 mas yr^{-1}. We also obtained the spatial velocities of a subset of the stars, as well as stellar masses from monitoring of binary systems.

Combining *Gaia* DR1 and radio astrometry, we found that distances and velocities of individual clouds in the Taurus complex change significantly across the cloud (Galli et al., 2018). The measurements revealed the depth of the cloud along the line of sight to be 36 pc. Later, we extended the sample of young stars with six-dimensional information by using *Gaia* DR2 astrometry and radial velocities from the literature (Galli et al., 2019). We found relative distances among the various clouds of 25 pc on average and relative space motions of a few km s^{-1}.

In Orion, the work by Kounkel et al. (2017) was one of the first studies that revealed the 3D structure of the cloud. Using VLBA data alone from GOBELINS, we found a distance gradient of about 40 pc between the ONC and L1641 and a similar value between NGC 2068 and NGC 2024. A prominent distance gradient of 30 pc from east to west was also found in the Perseus complex (Ortiz-León et al., 2018a) and a small distance gradient of 6 pc in Ophiuchus (Ortiz-León et al., 2018b). We also investigated the kinematical properties of the IC 348 and NGC 1333 clusters in Perseus (Ortiz-León et al., 2018a), finding that their internal motions are dominated by random motions, rather than by ordered motions due to expansion, contraction or rotation.

Finally, we derived the astrometry of water masers associated to a protostar in the very young ($\sim 2 \pm 1 \times 10^5$ yr) Serpens South cluster (Ortiz-León et al., 2023). No optical sources with good astrometric solutions were available in *Gaia* DR3. Thus, a direct distance determination was only possible thanks to the observations performed at radio wavelengths.

3. Astrometric Characterization of exoplanetary systems

Astrometric accuracy of tens of micro-arseconds (μas) has the potential to reveal the presence of hidden companions, which would induce a reflex motion on the star about the system's barycenter. Very Long Baseline Interferometry observations of the radio emission from nearby ($\lesssim$10 pc) low mass stars (M-dwarfs, ultracool dwarfs and brown dwarfs) have allowed us to search for companions with planetary masses. Using the VLBA, we discovered a Saturn-mass exoplanet associated to the ultracool dwarf TVLM 513–46546 (Curiel et al., 2020). This planet has a period of 221 ± 5 days and induces an astrometric signature (semi-major axis of the star's orbit) of 145 ± 20 μas.

We also performed VLBA observations of the M3.5+M4.5 binary GJ 896AB, detecting both components (Curiel et al., 2022). Fitting the positions of the primary star, including acceleration terms to take the perturbation of the secondary star into account, revealed significant residuals that suggest the presence of a new close companion orbiting the primary star. The absolute positions of the primary and secondary star, as well as the relative positions of the binary (from radio and optical data) were fitted simultaneously with a combined model that includes the new companion. We found a period of 284 ± 2 days and a mass of 2.3 ± 0.6 $M_{\rm Jup}$ for the planetary companion. The astrometric signature induced by the planet on the host star is 510 ± 150 μas. The true 3D orientation of the binary and planetary orbits is shown in Fig. 1. Using the angles obtained from the astrometric fittings we estimated a mutual inclination angle between the orbits of 148°.

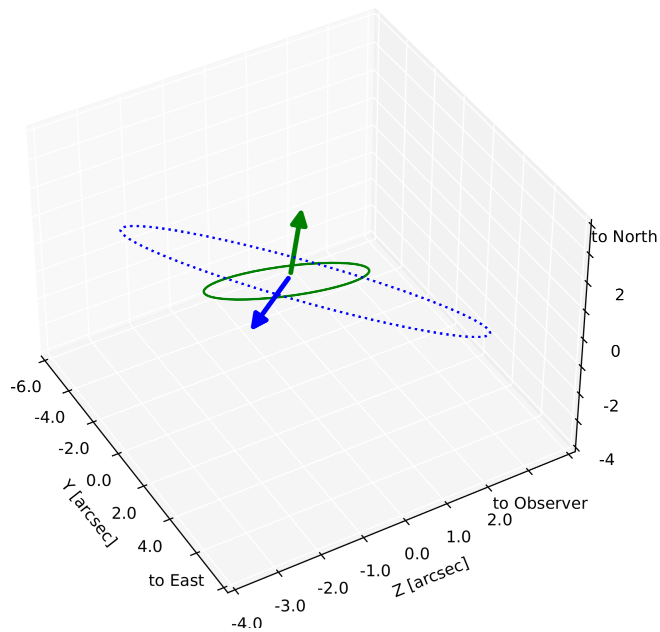

Figure 1. 3D representation of the binary (blue) and planetary (green) orbits in GJ 896. The arrows indicate the orbital angular momentum vectors. The planetary orbit has been scaled by a factor of 20.

4. FINAL REMARKS

Radio astrometry and *Gaia* have been fundamental for the characterization of molecular cloud 6D structure and the stellar systems that live within them. In the field of exoplanet exploration, high-precision astrometry is now making important contributions. The 3D shapes and the true inclination between planetary and binary orbits can be investigated. With more discoveries that next-generation instruments can bring, astrometry could help to better understand planet formation in single and binary stars and their dynamical evolution.

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