

Dynamical Masses of Young Stellar Multiple Systems with the VLBA (DYNAMO-VLBA)

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Abstract. Very Long Baseline Interferometry (VLBI) provides high angular resolution images and has been used for stellar astrometry for decades. The DYNAMO-VLBA project utilizes the Very Long Baseline Array (VLBA) to study tight binary and multiple pre-main sequence stars, whose components have detectable radio emission and typical separations on the order of milli-arcseconds. Such systems cannot be resolved by Gaia, making VLBI an essential tool for the study of their orbital parameters and, eventually, the determination of their mass. Here, we report VLBA dynamical mass measurements of the individual stars in the S1 system in Ophiuchus and EC 95 in Serpens. S1 is the most luminous and massive stellar member of the nearby Ophiuchus star-forming region. We find that the primary component, S1A, has a mass of $4.11 \pm 0.10 M_{\odot}$. This is significantly less than the value of $\sim 6 M_{\odot}$ expected from theoretical models given the location of S1A on the HR diagram. The secondary, S1B, has a mass of $0.831 \pm 0.014 M_{\odot}$ and is most likely a T Tauri star. In the Serpens triple system EC 95, we measure the masses of EC 95A and EC 95B, finding $2.15 \pm 0.10 M_{\odot}$ and $2.00 \pm 0.12 M_{\odot}$, respectively. In this case, the measured masses agree with the location of the stars in the HR diagram for very young $2 M_{\odot}$ stars. For the first time, we also estimated the mass of tertiary, EC 95C, to be $0.26^{+0.53}_{-0.46} M_{\odot}$.

1. Introduction

The precise measurement of stellar masses is fundamental for understanding star formation processes and stellar evolution. Young pre-main sequence stars in nearby regions offer a unique opportunity to study these processes in detail. However, determining the masses of these stars is challenging, especially when dealing with binary or multiple systems with very small separations. Very Long Baseline Interferometry (VLBI) provides high angular resolution images and has been used for stellar astrometry for decades. In particular, the *Very Long Baseline Array* (VLBA) is an essential tool for studying stellar systems with separations on the order of milliarcseconds, where space missions like *Gaia* cannot resolve individual components or provide information on their orbital parameters.

In the *Dynamical Masses of Young Stellar Multiple Systems with the VLBA* (DYNAMO-VLBA)¹ project, we use the VLBA to study binary and multiple pre-main sequence stars whose components have detectable radio emission. These observations allow us to measure the dynamical masses of individual stars without relying on assumptions about their physical parameters. This is

crucial for testing and refining theoretical evolutionary models of young stars.

One of the systems of particular interest is S1 in the Ophiuchus star-forming region. Located at a distance of 137.2 ± 0.4 pc (Ordóñez-Toro et al., 2024), S1 stands out as the brightest and most massive stellar member of this region. It was the first young stellar object directly detected using VLBI techniques (André et al., 1991). Lunar occultation experiments in the infrared (Richichi et al., 1994) and radio observations with the VLBA (Ortiz-León et al., 2017a) revealed that S1 is a binary stellar system with an angular separation on the order of 20 mas. Previous studies suggested that S1 is a young Herbig Be star with an estimated mass of 5 to $6 M_{\odot}$ based on photometric measurements (e.g., Lada & Wilking, 1984).

Another system of interest is EC 95 in the Serpens region, located at 436.0 ± 9.2 pc (Ortiz-León et al., 2018). EC 95 was initially classified as a proto-Herbig Ae/Be star of spectral type K2, with an approximate age of 10^5 years and an estimated mass of $\sim 4 M_{\odot}$ based on its location in the HR diagram (Preibisch, 1999). Radio observations with the VLBA revealed that EC 95 is a binary system with a separation of approximately 15 mas (Dzib et al., 2010). These observations indicated that the system consists of two components, EC 95A and EC 95B,

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¹ <https://www3.mpifr-bonn.mpg.de/div/radiobinaries/intro.php>

and suggested a significantly higher mass for the primary. Additionally, a third component, EC 95C, was detected in near-infrared observations with the VLT (Duchêne et al., 2007) and in radio observations with the VLBA (Ortiz-León et al., 2017b), making EC 95 a hierarchical triple system where each component shows non-thermal radio emission.

2. Observations and Data Reduction

Observations of the stellar systems S1 and EC 95 were carried out using the VLBA of the National Radio Astronomy Observatory (NRAO) as part of the DYNAMO-VLBA project (VLBA project code: BD215). The observations recorded the radio continuum flux at a wavelength of $\lambda = 6.0$ cm ($\nu = 5$ GHz). The data calibration followed standard procedures for phase referenced VLBI observations and was performed using the Astronomical Image Processing System (AIPS) software (Greisen, 2003). These procedures have been detailed in previous works (e.g., Loinard et al., 2007; Dzib et al., 2010; Ortiz-León et al., 2017a). Flux densities and positions of detected sources were measured using a two-dimensional Gaussian fitting procedure (task JMFIT in AIPS).

In addition to the DYNAMO-VLBA observations, we included archival VLBA observations of S1 and EC 95 in our analysis. For S1, this includes data from the Gould Belt Distances Survey (GOBELINS) previously reported by Loinard et al. (2008); Ortiz-León et al. (2017a, 2018). For EC 95, archival data from projects by Dzib et al. (2010), and the GOBELINS survey were used (Ortiz-León et al., 2017b). In total, we analyzed 35 epochs for S1 and 32 epochs for EC 95, spanning more than a decade of observations for each source.

3. Astrometric Fitting Procedure

The motion of the components of a binary stellar system on the celestial sphere can be described by the combination of their common trigonometric parallax π , the uniform proper motion of their center of mass in right ascension (μ_α) and declination (μ_δ), and their orbital motions around the center of mass. For the primary component, the equations of motion are expressed as:

$$\alpha(t) = \alpha_0 + \mu_\alpha t + \pi f_\alpha(t) + a_1 Q_\alpha(t), \quad (1)$$

$$\delta(t) = \delta_0 + \mu_\delta t + \pi f_\delta(t) + a_1 Q_\delta(t), \quad (2)$$

In these equations, $f_\alpha(t)$ and $f_\delta(t)$ correspond to the projections of the parallax ellipse in right ascension and declination, while $Q_\alpha(t)$ and $Q_\delta(t)$ represent the projections of the orbital motions. The detailed expressions are provided in Ordoñez-Toro et al. (2024). With appropriate minor adjustments, similar equations hold for the secondary component.

To estimate the astrometric and orbital parameters of the binary system, we follow the procedure described in Ordoñez-Toro et al. (2024). We applied the MPFIT least

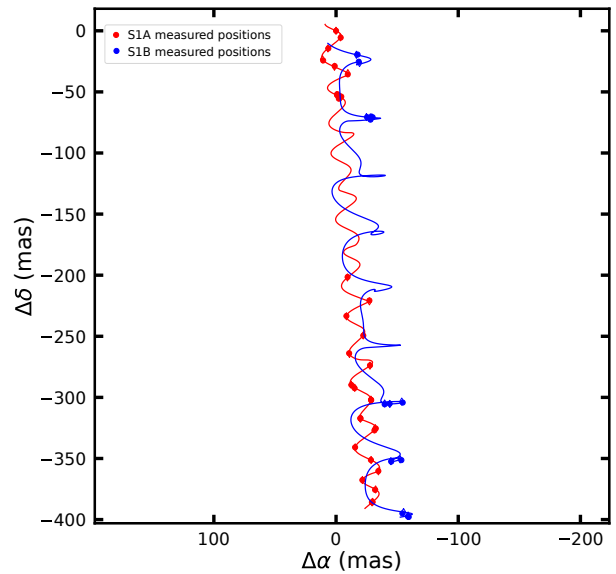


Fig. 1. Measured positions of S1A (red dots) and S1B (blue dots) shown as offsets from the position of S1A in the first detected epoch (2005 June 24). Figure from Ordoñez-Toro et al. (2024).

squares fitting algorithm (see also Kounkel et al., 2017, and references therein), which fits the observed positions to the equations of motion. This approach allows us to determine the total mass of the system from Kepler’s third law and the individual masses of the stars by accounting for their motions relative to the center of mass.

4. Results

4.1. Binary system S1

Our VLBA observations, combined with archival data, resulted in a total of 35 epochs. The primary component, S1A, was detected in all 35 epochs, while the secondary component, S1B, was detected in 14 epochs.

We determined that S1A has a mass of $4.11 \pm 0.10 M_\odot$, significantly less than the previously reported $6 M_\odot$. This highlights a discrepancy where models corresponding to the location of S1A on the HR diagram predict masses at least 25% higher than the dynamical mass. The secondary, S1B, has a mass of $0.831 \pm 0.014 M_\odot$, consistent with a low-mass star. Figure 1 shows the measured positions of S1A and S1B. In Figure 2, we present the relative positions of S1B with respect to S1A, along with the orbital fit model.

4.2. Binary system EC 95

For the EC 95 system, our combined observations provided 32 epochs for EC 95A and EC 95B. The primary component, EC 95A, was detected in all 32 epochs, and the secondary component, EC 95B, was detected in 23 epochs.

We measured the masses of EC 95A and EC 95B to be $2.15 \pm 0.10 M_\odot$ and $2.00 \pm 0.12 M_\odot$, respectively.

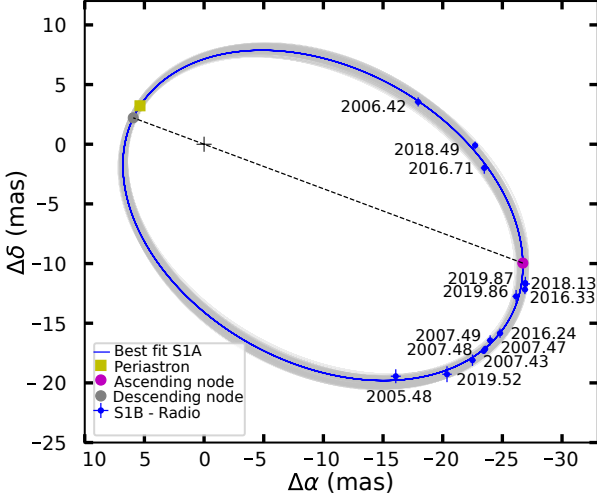


Fig. 2. Stellar relative positions and orbital fit model of S1. The blue dots indicate the relative positions of S1B with respect to S1A, and the errorbars consider the position errors of both components which are added in quadrature. The dashed black line traces the line of nodes from the model, and the black cross indicates the position of the primary.

Additionally, we detected the third component, EC 95C, combining four epochs of observations from infrared data (Duchêne et al., 2007) and VLBA measurements. For the first time, we estimated the mass of EC 95C to be $0.26^{+0.53}_{-0.46} M_{\odot}$ with an orbital period of 172 ± 14 years.

Figure 3 displays the measured positions of EC 95A and EC 95B. In Figure 4, we present the relative positions of EC 95B with respect to EC 95A, along with our orbital fit model. Furthermore, Figure 5 shows the orbital configuration of the entire system, including the components A, B, and C around the center of mass.

5. Discussion and Conclusions

In this work, we presented new VLBA observations of the S1 and EC 95 systems, combined with archival data, to improve the constraints on the dynamical masses of the individual stars in these young stellar multiple systems.

For the S1 system, our analysis determined that the primary component, S1A, has a dynamical mass significantly less than previous estimates based on photometric measurements (e.g., Lada & Wilking, 1984). This discrepancy shows that theoretical models corresponding to the location of S1A on the HR diagram overpredict the mass by at least 25%. By considering models that incorporate rotation (specifically the PARSEC pre-main sequence models of Nguyen et al. 2022), we show that rotation does not reconcile the HR diagram position of S1A with its dynamical mass measurement (Ordóñez-Toro et al., 2024). Therefore, refinements in the evolutionary models for young intermediate-mass stars like S1A are necessary to reconcile these differences. The secondary component,

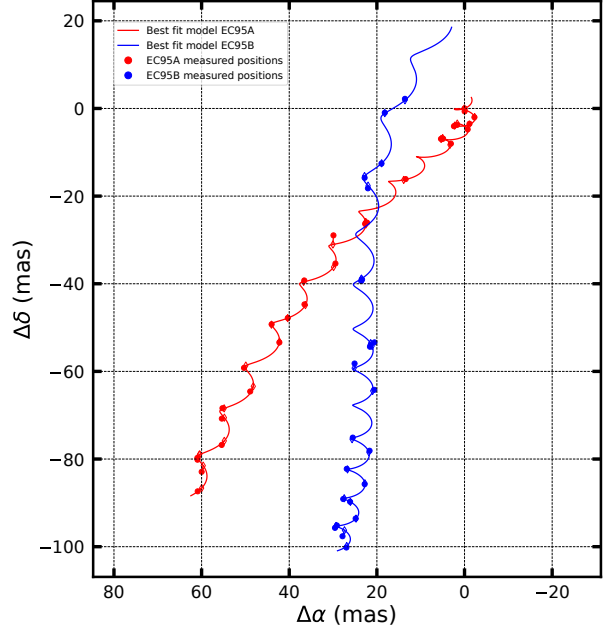


Fig. 3. Measured positions of EC 95A (red dots) and EC 95B (blue dots) shown as offsets from the position of EC 95A in the first detected epoch (2007 December 22). Figure from Ordoñez-Toro et al. (submitted).

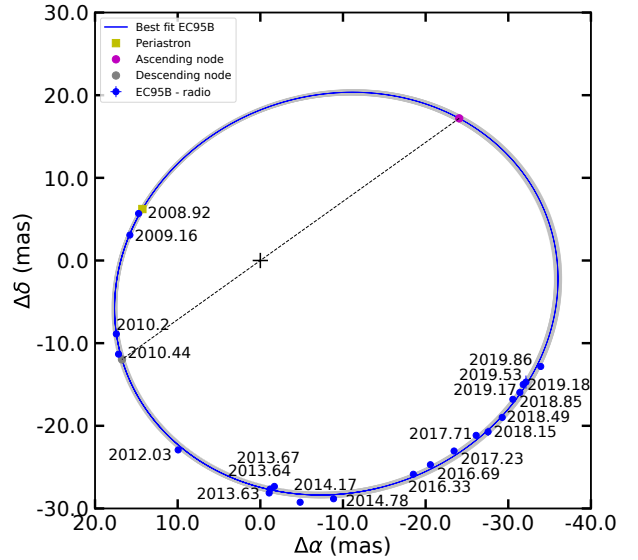


Fig. 4. Stellar relative positions and orbital fit model of EC 95. The blue dots indicate the relative positions of EC 95B with respect to EC 95A. The remaining description is similar to that provided for the S1 Figure 2. Figure from Ordoñez-Toro et al. (submitted).

S1B, is consistent with a low-mass T Tauri star.

For the EC 95 system, we found that the dynamical masses of the primary and secondary components are consistent with each other and with early stellar evolution models. This agreement supports the reliability of current pre-main sequence evolutionary tracks for low-mass stars.

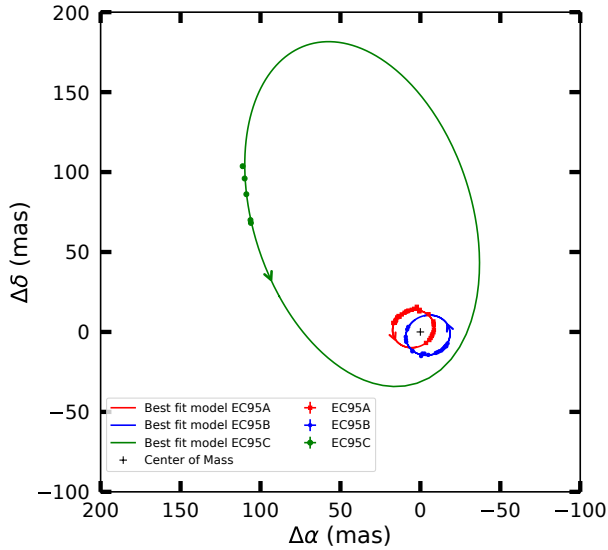


Fig. 5. Orbits of EC 95A (red line), EC 95B (blue line) and EC 95C (green line) around the center of mass of the system (black cross). The colored squares indicate the measured positions, while the arrows show the direction of the orbits. Figure from Ordoñez-Toro et al. (submitted).

Our detection of the third component in the EC 95 system (EC 95C) and the constraints we obtain on its orbit also enable us to discuss the architecture of the entire system. We find that the inclinations of the inner binary orbit (AB) and the orbit of EC 95C around the barycenter of AB are both approximately 35° , which is consistent with a hierarchical system formed through disk fragmentation (Adams et al., 1989). However, the significant eccentricities of both orbits ($e = 0.391 \pm 0.003$ for AB and $e = 0.75 \pm 0.03$ for EC 95C) and the misalignment of their semi-major axes raise questions about the hierarchical stability of the system. The orientations of the semi-major axes, with $\omega = 117.27 \pm 0.51$ degrees and $\Omega = 305.56 \pm 1.13$ degrees for AB, and $\omega = 43.49^{+11.03}_{-7.34}$ degrees and $\Omega = 169.23^{+7.71}_{-12.44}$ degrees for EC 95C, further emphasize these challenges. As seen in Figure 5, near periastron, the separation between EC 95C and the AB barycenter becomes comparable to the separation between EC 95A and EC 95B, potentially leading to dynamical instability. It is important to note that the limited orbital coverage of EC 95C introduces uncertainties in its orbital elements. Future resolved observations at radio and infrared wavelengths will be crucial to assess the long-term stability of the system.

Overall, our study emphasizes the importance of precise dynamical mass measurements in young close binary systems and demonstrates the effectiveness of VLBA observations in achieving this goal. These results help to constrain pre-main sequence stellar evolution models and improve our understanding of stellar formation and evolution in multiple systems.

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