Dynamical Masses of Pre-Main-Sequence Binary Systems

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Abstract. We present results of our ongoing monitoring program for orbital motion of T Tauri binaries. Their companions were discovered in the 1990s. With projected separations of 15 – 42 AU, the expected orbital periods range from 60 to 250 years. We have collected observations using speckle interferometry, adaptive optics, and lucky imaging. About 16 companions have clearly moved since their discovery, about 10 of them show signs of curvature characteristic for orbital motion. For a few binaries, it is already possible to solve for a (very) preliminary orbit solution.

1. Introduction

The mass is probably the most important parameter for the structure and evolution of a star. For a pre-main-sequence (PMS) star, it is usually estimated by the star's location in the Hertzsprung-Russell diagram relative to theoretical model calculations of PMS evolution. Unfortunately, for stars less massive than $\sim 1.5\,M_\odot$, these estimates vary depending on the calculations used (e.g. Simon 2008; Hillenbrand & White 2004).

Therefore, model-independent mass determinations are crucial for our understanding of stellar astrophysics. If we determine the orbit of a binary star with a known distance, we also get its mass. This is the only way to measure stellar masses directly, without relying on theoretical models. Binary stars are therefore valuable test cases for theoretical pre-main-sequence tracks.

In the 1990s, a number of multiplicity surveys among T Tauri stars have been performed, providing us with a sample of visual binaries with separations of $0.1 - 0.3''$ (Ghez et al. 1993; Leinert et al. 1993; Köhler & Leinert 1998). At distances of 140 pc and projected separations of 15 – 42 AU, the expected orbital periods range from 60 to 250 years.

We are monitoring a number of close visual binaries in the star-forming region Taurus-Auriga, with the goal to determine their orbits and ultimately their masses.

2. Observations

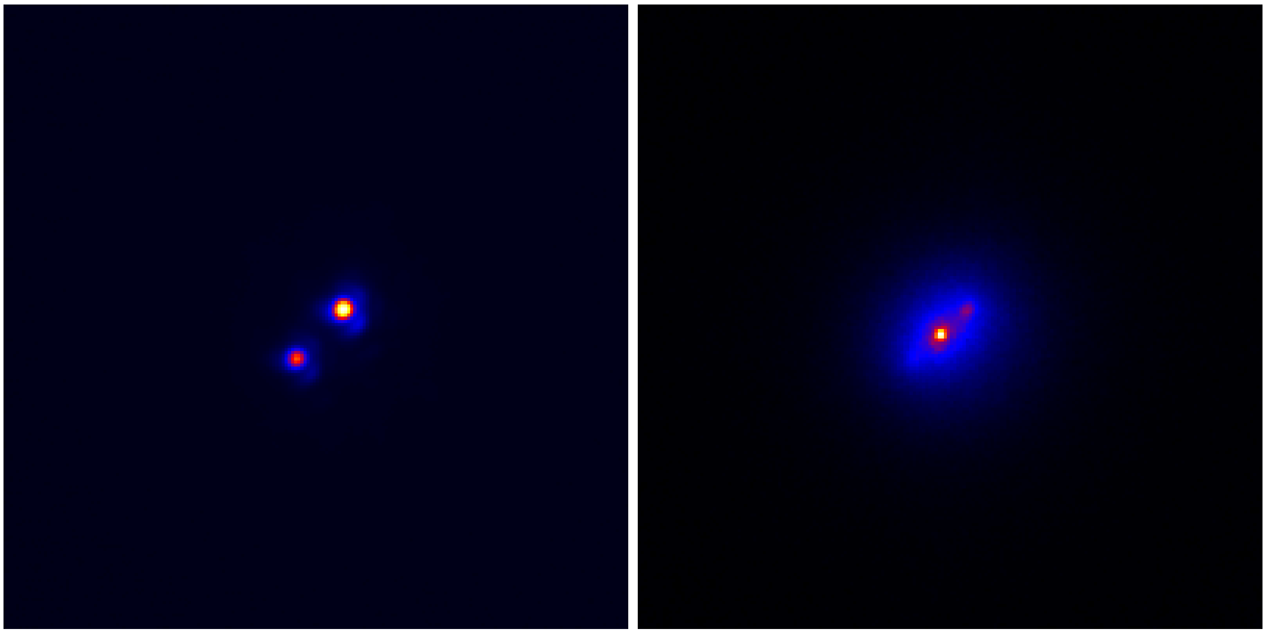

Figure .1: Images of XZ Tau taken with NACO in the Ks-band in November 2006 (left) and with AstraLux through the SDSS z′ filter in October 2013 (right). North is up, and East to the left. The separation of the two stars is about 0.3 arcsec. Note that the field of view of the two images is not the same.

For our monitoring program of close binaries, we used different telescopes and instruments:

- the adaptive optics (AO) system at the 3 m Shane Telescope of Lick observatory on Mount Hamilton, California (Bauman et al. 2002),
- the AO-system NAOS/Conica (NACO) at ESO's 8 m Very Large Telescope on Paranal, Chile (Lenzen et al. 2003; Rousset et al. 2003),
- the lucky imaging camera AstraLux at the 2.2 m telescope on Calar Alto, Spain (Hormuth et al. 2008).

Figure .1 shows examples of the resulting images.

We paid particular attention to the astrometric calibration of the cameras. During each observing run, a field near the trapezium in the Orion Nebula Cluster was observed. The pixel positions of the cluster stars were compared to the coordinates given in Close et al. (2012), which in turn are based on HST-positions of a few cluster stars. We computed the mean pixel scale and orientation of the detector from a global fit of all star positions. The scatter of values derived from star pairs were used to estimate the errors.

Table .1: Period and mass estimates, based on circular orbit models

Name	Period estimate [years]	Mass estimate [$M_\odot$]
BD+26 718B	1200	1.3
FO Tau	170	0.8
FS Tau	3000	21
HD 284135	220	3.3
HK Tau G2	210	0.8
IS Tau	190	1.1
IW Tau	320	1.7
LkHα332 G1	220	0.8
RX J0430.8+2113	72	59
RX J0444.4+1952	68	14
UZ Tau w	420	0.8
XZ Tau	1060	1.0

3. Results

Many of the close binary T Tauri stars in Taurus-Auriga show changes in their relative positions. However, none of the stars in our monitoring program has moved enough for a full orbit fit. In order to get an estimate for the binary periods, we fit circular orbits to the data. The fitting procedure is the same as described in, e.g., Köhler et al. (2013), except that only orbit models with eccentricity zero were used. The results for the cases where the fit converged are listed in table .1. Most of the mass estimates appear plausible, although our experience with incomplete orbit fits shows that more data can change the result by a factor of 2 or more.

Some of the estimated masses (FS Tau, RX J0430.8+2113, and RX J0444.4+1952) do not agree with the mass expected for a star of their spectral type. In general, this indicates that more observations are required to determine the orbit.

However, Sebastian Daemgen pointed out during the workshop that this could also be the result of an overestimated distance to the systems. In particular, RX J0444.4+1952 might not be a member of the Taurus-Auriga star-forming region, but a young foreground star. Since the dynamical mass is proportional to the third power of the semi-major axis (which is proportional to the distance of the system), a change in distance by a factor of 2 results in a mass that is off by almost an order of magnitude.

From the spectral type of RX J0444.4+1952, we would expect the system mass to be about 0.86 $M_\odot$ (Daemgen, priv. comm.). The mass depends only weakly on the age and is nearly the same for an age between 2 and 20 Myr. Our dynamical mass estimate would also be 0.86 $M_\odot$ if the distance to the binary was only about 55 pc instead of the canonical distance to Taurus-Auriga of 140 pc.

The spectral type of the second star with an implausible large mass, RX J0430.8+2113, is G8 (Wichmann et al. 1996). At this spectral type, the mass depends strongly on the age.

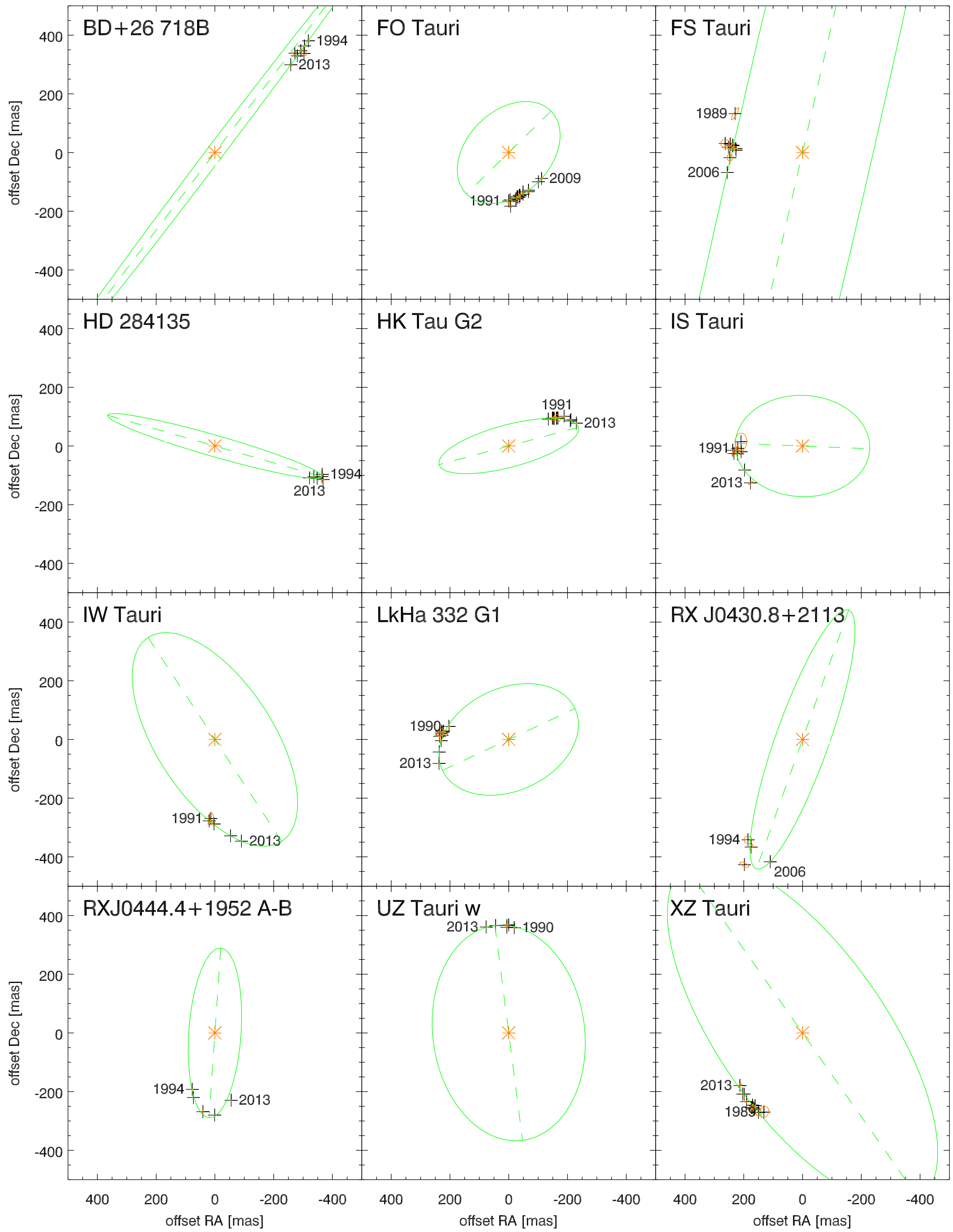

Figure .2: Orbits of the stars that have moved far enough to solve for a preliminary orbit. The observed positions are marked by their error ellipses. The year of the first and latest observation is given. The green ellipse shows the best-fitting circular orbit. The dashed line marks the line of nodes.

It is about $3.5\,M_\odot$ at 1 Myr, but only about $1.2\,M_\odot$ at 20 Myr. At a distance of 55 pc, our dynamical mass would be $3.6\,M_\odot$. However, a star of this mass would be much brighter than observed. The star is either even closer than 55 pc, or our orbit fit is still far from the true orbit (which we consider to be the more likely explanation).

4. Outlook

We will continue to monitor the close young binaries in Taurus-Auriga and other star-forming regions. The next AstraLux observations are scheduled for November 2014. With astrometric measurements collected in a few more years, we expect to be able to carry out full orbit fits for some of our targets. By then, *Gaia* will have provided precise parallaxes, which will resolve the uncertainty of the distance.

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References

Bauman, B. J., Gavel, D. T., Waltjen, K. E., et al. 2002, in Proc. SPIE, Vol. 4494, Adaptive Optics Systems and Technology II, ed. R. K. Tyson, D. Bonaccini, & M. C. Roggemann, 19–29

Close, L. M., Puglisi, A., Males, J. R., et al. 2012, ApJ, 749, 180

Ghez, A. M., Neugebauer, G., & Matthews, K. 1993, AJ, 106, 2005

Hillenbrand, L. A. & White, R. J. 2004, ApJ, 604, 741

Hormuth, F., Hippler, S., Brandner, W., Wagner, K., & Henning, T. 2008, in Proc. SPIE, Vol. 7014, Ground-based and Airborne Instrumentation for Astronomy II, ed. I. S. McLean & M. M. Casali, 48

Köhler, R. & Leinert, C. 1998, A&A, 331, 977

Köhler, R., Ratzka, T., Petr-Gotzens, M. G., & Correia, S. 2013, A&A, 558, A80

Leinert, C., Zinnecker, H., Weitzel, N., et al. 1993, A&A, 278, 129

Lenzen, R., Hartung, M., Brandner, W., et al. 2003, in Proc. SPIE, Vol. 4841, Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, ed. M. Iye & A. F. M. Moorwood, 944–952

Rousset, G., Lacombe, F., Puget, P., et al. 2003, in Proc. SPIE, Vol. 4839, Adaptive Optical System Technologies II, ed. P. L. Wizinowich & D. Bonaccini, 140–149

Simon, M. 2008, in The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation Instrumentation, ed. A. Richichi, F. Delplancke, F. Paresce, & A. Chelli, 227

Wichmann, R., Krautter, J., Schmitt, J. H. M. M., et al. 1996, A&A, 312, 439