The Orbit of GG Tau A

R. Köhler

1 Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany, e-mail: koehler@mpia.de
2 Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Königstuhl, 69117 Heidelberg, Germany, e-mail: r.koehler@lsw.uni-heidelberg.de

Received 15 December 2010; accepted 12 April 2011

ABSTRACT

Aims. We present a study of the orbit of the pre-main-sequence binary system GG Tau A and its relation to its circumbinary disk, in order to find an explanation for the sharp inner edge of the disk.

Methods. Three new relative astrometric positions of the binary were obtained with NACO at the VLT. We combine them with data from the literature and fit orbit models to the dataset.

Results. We find that an orbit coplanar with the disk and compatible with the astrometric data is too small to explain the inner gap of the disk. On the other hand, orbits large enough to cause the gap are tilted with respect to the disk. If the disk gap is instead caused by the stellar companion, then the most likely explanation is a combination of underestimated astrometric errors and a misalignment between the planes of the disk and the orbit.

Key words. Stars: pre-main-sequence – Stars: individual: GG Tauri A – Stars: fundamental parameters – Binaries: close – Astrometry – Celestial Mechanics

1. Introduction

GG Tau is a young quadruple system consisting of two binaries (Leinert et al. 1993). GG Tau A is a pair of low-mass stars separated by about 0.25″. GG Tau B, located 10.1″ to the south, is wider (1.48″) and less massive. A circumbinary disk around GG Tau A has been extensively studied. It was spatially resolved in both near infrared and millimeter wavelength domains. A detailed analysis of the velocity maps of the disk found that it is in Keplerian rotation and constrained the central mass to \(1.28 \pm 0.07 \, M_\odot\) (Guilloteau et al. 1999).

So far, orbital motion has not been detected in the GG Tau B binary because of its long period. However, the relative motion of the components of GG Tau A has been observed for several years and has already resulted in several orbit determinations (McCabe et al. 2002; Tamazian et al. 2002; Beust & Dutrey 2005). Because only a limited section of the orbit has been observed, the authors generally have assumed that the orbit is coplanar with the circumstellar disk (\(i = 37° \pm 1°\)). The resulting orbital parameters were all quite similar to each other, with a semi-major axis of about 35 AU.

The presence of the binary would be an obvious explanation for the rather sharp inner edge of the disk located at 180 AU. The ratio of the inner radius of the disk and the semi-major axis is about five. However, Artymowicz & Lubow (1994) studied the effect of binary systems on their circumbinary disks and found that this ratio should range from about 1.7 (for circular orbits) to about 3.3 (for highly eccentric binaries, \(e = 0.75\)). Beust & Dutrey (2005, 2006) carried out a similar study specifically for GG Tau A and came to the same conclusion. The binary orbit cannot explain the gap in the circumbinary disk, unless its semi-major axis is about twice as large as indicated by the astrometric data available.

In this paper, we present new relative astrometric measurements of GG Tau A and derive estimates for its orbital parameters, with and without the assumption that binary orbit and circumbinary disk are coplanar.

2. Observations and data reduction

Astrometric measurements of GG Tau A have been published by several authors (Duchêne et al. 2004; Ghez et al. 1995, 1997; Hartigan & Kenyon 2003; Krist et al. 2002; Leinert et al. 1993; McCabe et al. 2002; Roddier et al. 1996; Tamazian et al. 2002; White & Ghez 2001; Woitas et al. 2001), see Beust & Dutrey (2005) for an overview. Here we report on new observations obtained with NAOS/CONICA (NACO for short), the adaptive optics, near-infrared camera at the ESO Very Large Telescope on Cerro Paranal, Chile (Rousset et al. 2003; Lenzen et al. 2003). GG Tau was observed on December 13, 2003 (PI: Leinert), November 20, 2006 (PI: Ratzka), and October 5, 2009 (PI: Köhler). We use only imaging observations in the K, photometric band for the orbit determination. Integration times were 85 sec per image in 2003, 24 sec in 2006, and 60 sec in 2009. In 2003 and 2006, we took four images with the star at different positions on the detector to facilitate creation of a median sky image. In 2009, 12 images were recorded at four positions.

The NACO images were sky subtracted with a median sky image, and bad pixels were replaced by the median of the closest good neighbors. Finally, the images were visually inspected for any artifacts or residuals. Figure 1 shows an example of the results.

The Starfinder program (Diolaiti et al. 2000) was used to measure the positions of the stars. The positions in several images taken during one observation were averaged, and their stan-
sioning of the science target, indicating the importance of a proper
astrometric calibration.

The calibrated separations and position angles of GG Tau A
appear in Table 1, together with the data taken from the litera-
ture. If one or both components of GG Tau B were within the
field-of-view, then we also measured their positions. The results
appear in Table 2. The main conclusion is that there has been no
significant change in the relative position since the first measure-
ment published in Leinert et al. (1993).

3. Determination of orbital elements

McCabe et al. (2002) and Beust & Dutrey (2005) have deter-
mined the orbital elements of GG Tau Aa-Ab from the aver-
age position and velocity of the companion. Together with the
system mass, position and velocity on the sky comprise five measure-
ments. Since orbital elements are seven unknowns, their computa-
tion requires the additional assumption that the orbit and the circumbinary disk are coplanar.

In this work, we employed a different approach. We fit or-
bit models to the observations and searched for the model with
the minimum $\chi^2$. In the end, we wanted to use a Levenberg-
Marquardt algorithm (Press et al., 1992). However, the results
of this algorithm depend strongly on the chosen start values. To
avoid any bias for a particular orbit, we carried out a prelimi-
ary fit that consists of a grid search in eccentricity $e$, period $P$, and
time of periastron $T_0$. Singular value decomposition was used to
solve for the remaining four elements. The result is a grid of $\chi^2$ as
function of $e$ and $P$. Since we were interested in the semi-
major axis $a$ of the orbit, this was converted onto a $a$-$e$-grid by

Table 1. Astrometric measurements of GG Tau Aa – Ab

| Date (UT)     | $d$ [mas] | PA ['] | Reference               |
|--------------|-----------|--------|-------------------------|
| 1990 Nov 2   | $255 \pm 10$ | $9 \pm 2$ | Leinert et al. (1993)   |
| 1991 Oct 21  | $260 \pm 10$ | $2 \pm 1$ | Ghiz et al. (1995)      |
| 1993 Dec 26  | $260 \pm 10$ | $3 \pm 2$ | Roddier et al. (1996)   |
| 1994 Jan 27  | $246 \pm 4$  | $357.8 \pm 0.4$ | Woitas et al. (2001)   |
| 1994 Jul 25  | $250.2 \pm 2.6$ | $358.8 \pm 0.45$ | Ghiz et al. (1997)    |
| 1994 Sep 24  | $258 \pm 4$  | $357. \pm 2$ | Ghiz et al. (1995)      |
| 1994 Oct 18  | $242 \pm 3$  | $0.9 \pm 0.5$ | Ghiz et al. (1995)      |
| 1994 Dec 22  | $239 \pm 5$  | $357.2 \pm 2$ | Roddier et al. (1996)   |
| 1995 Oct 8   | $247 \pm 4$  | $356.9 \pm 0.7$ | Woitas et al. (2001)   |
| 1996 Sep 29  | $245 \pm 4$  | $355.5 \pm 0.4$ | Woitas et al. (2001)   |
| 1996 Dec 6   | $243.6 \pm 4.6$ | $354.9 \pm 1.3$ | White & Ghiz (2001)    |
| 1997 Sep 27  | $250 \pm 3$  | $354.3 \pm 1$  | Krist et al. (2002)     |
| 1997 Oct 10  | $248 \pm 2$  | $353.9 \pm 0.4$ | McCabe et al. (2002)   |
| 1997 Nov 16  | $247 \pm 5$  | $353.6 \pm 0.4$ | Woitas et al. (2001)   |
| 1998 Oct 10  | $260 \pm 4$  | $350.7 \pm 0.4$ | Woitas et al. (2001)   |
| 2001 Jan 21  | $248 \pm 14$ | $348.6 \pm 2.4$ | Hartigan & Kenyon (2003) |
| 2001 Feb 9   | $245 \pm 4$  | $347.8 \pm 0.3$ | Tamazian et al. (2002) |
| 2002 Dec 12  | $250.7 \pm 1.5$ | $346.0 \pm 1.5$ | Duchêne et al. (2004)   |
| 2003 Dec 13  | $250.7 \pm 0.8$ | $344.2 \pm 0.1$ | this work              |
| 2006 Nov 20  | $252.3 \pm 0.7$ | $339.0 \pm 0.1$ | this work              |
| 2009 Oct 5   | $252.5 \pm 0.3$ | $334.5 \pm 0.1$ | this work              |

Table 2. Astrometric measurements of GG Tau B

| Date (UT)     | Pair | $d$ [arcsec] | PA ['] | Reference               |
|--------------|------|--------------|--------|-------------------------|
| 2006 Nov 20  | Bb–Ba| $1.460 \pm 0.002$ | $134.9 \pm 0.1$ | this work              |
| 2006 Nov 20  | Aa–Ba| $10.07 \pm 0.01$  | $185.4 \pm 0.1$ | this work              |
| 2009 Oct 5   | Aa–Ba| $10.09 \pm 0.01$  | $185.5 \pm 0.1$ | this work              |

finding the orbit model with the closest $a$ for each grid point.
The grid spans a range from 20 to 200 AU in $a$, and from 0 to 0.99 in $e$.

To convert the measured separations into AU, a distance of
140 pc was adopted (Elias, 1978).

3.1. Orbits coplanar with the disk

First, we searched for an orbit matching all the informa-
tion available, i.e. the astrometric position, the total mass, and the ori-
tentation of the disk plane. We assumed that disk and orbit are
coplanar, orbits without this constraint are discussed in the next
section.

The $\chi^2$ that we try to minimize is

$$\chi^2 = \sum_i \left( \frac{r_{\text{obs}} - r_{\text{model}}}{\Delta r_{\text{obs}}} \right)^2 + \left( \frac{M_{\text{est}} - M_{\text{model}}}{\Delta M_{\text{est}}} \right)^2$$

$$+ \left( \frac{\Delta \Omega_{\text{disk}} - \Omega_{\text{model}}}{\Delta \Omega_{\text{model}}} \right)^2,$$

where $r_{\text{obs}}$ and $r_{\text{model}}$ are the measured and predicted position
at the time of observation $i$, and $\Delta r_{\text{obs}}$ is the error of the measure-
ment. Here, $M_{\text{est}}$ is the measured system mass ($1.28 \pm 0.07 M_{\odot}$; Gui
lloteau et al., 1999), and $M_{\text{model}}$ the system mass predicted by the orbit model. Then, $\Delta \Omega_{\text{disk}}$ and $\Delta \Omega_{\text{model}}$ are the incli-
nation and position angle (PA) of the ascending node of the orbit
of a disk particle, $\Delta \Omega_{\text{disk}}$ and $\Delta \Omega_{\text{model}}$ are their errors. The inclina-
tion of the disk is $37 \pm 1^\circ$ (Guilloteau et al., 1999), but it is in

Fig. 1. Image of GG Tau A obtained with NACO in October 2009. The separation between the two components is about 250 mas.
Fig. 2. $\chi^2$ as function of $a$ and $e$ for orbit models that are coplanar with the circumbinary disk (Sect. 3.1). The cross at $a = 34$ AU, $e = 0.28$ marks the minimum, the contour line around it encircles the 99.7% confidence region (corresponding to $3\sigma$ in the case of normally distributed errors). The areas in various shades of gray are within the 5$\sigma$ confidence region, i.e. orbit models in the white area can be excluded with 5$\sigma$ confidence.

Fig. 3. Best-fitting orbit model if the orbit is constrained to be coplanar with the circumbinary disk (Sect. 3.1). The observed positions are marked by their error ellipses and lines connecting the observed and calculated position at the time of the observations. The new observations with NACO are marked by crosses. Their errors are too small to be discernible. The dash-dotted line indicates the line of nodes, the dashed line the periastron, and the arrow shows the direction of the orbital motion.

retrograde rotation, so $i_{\text{disk}} = 180 - 37 = 143^\circ$. The PA of the minor axis of the disk is $7 \pm 2^\circ$ (Guilloteau et al., 1999), therefore $\Omega_{\text{disk}} = 277 \pm 2^\circ$ (the ascending node is defined as the point in the orbit where the object is receding from the observer most rapidly, e.g. Hilditch, 2001).

Fig. 4. $\chi^2$ as function of $a$ and $e$ for orbit models that are not necessarily coplanar with the circumbinary disk (Sect. 3.2). As in Fig. 2, the minimum $\chi^2$ is marked by the cross, but the contour line around it encircles the 68.3% confidence region ($1\sigma$). The areas in shades of gray are within the 5$\sigma$ confidence region. The jagged shape of the contour line is most likely caused by numerical effects.

Fig. 5. Three exemplary orbit models that fit the astrometric data and the system mass, but are not coplanar with the disk. The semi-major axes of the orbits are 35 AU, 85 AU, and 137 AU. The last orbit has the minimal $\chi^2$, and its line of nodes is marked by the dash-dotted line and its periastron by the dashed line. The observed positions are marked by their error ellipses and lines connecting the observed and calculated position at the time of the observations. The new observations with NACO are marked by crosses. Their errors are too small to be discernible.

Equation was minimized by a Levenberg-Marquardt algorithm (Press et al., 1992). The starting points for the algorithm were taken from the preliminary fit described in the previous section. We kept $a$ and $e$ fixed to preserve the grid in these two variables. The resulting $\chi^2$ distribution is depicted in Fig. 2. There
is a clear minimum at \( a = 34 \text{ AU} \) and \( e = 0.28 \), while orbits with \( a > 36 \text{ AU} \) can be excluded on the 3\( \sigma \) level. This is in perfect agreement with previous orbit determinations. The reduced \( \chi^2 \) at the minimum is 3.05, which indicates a less-than-perfect fit. Figure 2 shows the orbit with the minimum \( \chi^2 \), together with the measurements of the relative positions, and Table 3 lists the orbital elements.

To test whether the astrometric errors were underestimated, we repeated the procedure, but enlarged the errors of the observations by a factor of 3. This lowers \( \chi^2 \) in general, but does not result in significant changes of the shape of the \( \chi^2 \)-plane as function of \( a \) and \( e \). The best-fitting orbit has now \( a = 40 \text{ AU} \) and \( e = 0.13 \). Also, because of the lower \( \chi^2 \), many orbits with \( a > 36 \text{ AU} \) (up to the end of the grid at \( a = 200 \text{ AU} \)) are within the 99.7\% confidence region (which corresponds to 3\( \sigma \) in the case of a normal distribution). However, it appears unlikely that the authors of all astrometric data underestimated their errors by such a large factor, and orbits large enough to cause the disk gap are still only marginally consistent with the data.

3.2. Orbits with no constraint on their orientation

In this section, we remove the constraint that the orbit has to be in the same plane as the circumbinary disk. The only constraints are therefore the astrometric measurements, and the total mass of the binary. Then, \( \chi^2 \) is given by (using the same symbols as in Eq. 1):

\[
\chi^2 = \sum_i \left( \frac{r_{\text{obs}} - r_{\text{model}}}{\Delta r_{\text{obs}}} \right)^2 + \left( \frac{M_{\text{est}} - M_{\text{model}}}{\Delta M_{\text{est}}} \right)^2.
\]

Figure 4 shows the result of minimizing the \( \chi^2 \) given by Eq. 2. The formal minimum is at \( a = 137 \text{ AU} \), \( e = 0.75 \) (Table 3), with a reduced \( \chi^2 \) of 3.2. It is highly unlikely that the true orbit has such a large semi-major axis and high eccentricity. However, the minimum is very shallow, and no semi-major axis larger than about 30 AU can be excluded, not even at the 1\( \sigma \) level. Figure 5 shows the orbit with the formally minimal \( \chi^2 \), and two orbits that result in the best fit if the semi-major axis is held fixed at 35 AU and 85 AU, respectively. All three orbits fit the measured data reasonably well, demonstrating that the semi-major axis is not well constrained by the astrometric data.

4. Discussion and conclusions

If we require the orbit model to lie in the same plane as the circumbinary disk, then orbits consistent with the astrometric data are not large enough to explain the gap in the disk. On the other hand, if we consider orbits that are not coplanar with the disk, then the astrometric data only provides a very weak constraint for the semi-major axis. This means that we can easily find orbits that are consistent with the measured positions and with the size of the gap in the circumbinary disk.

According to Artymowicz & Lubow (1994), an orbit with eccentricity \( e = 0.4 \ldots 0.5 \) can open a disk gap that is a factor of about 3 larger than its semi-major axis. For our disk with an inner edge at about 180 AU, a semi-major axis of 60 AU would suffice. Figure 6 shows that orbits with \( a = 60 \text{ AU} \) should have an eccentricity of \( 0.4 \ldots 0.45 \) to match the astrometric data. We consider this to be the most plausible orbit, given the constraints from the astrometric data and the size of the disk gap. Its orbital elements appear in the rightmost column of Table 3.

---

1 They use a slightly different notation, where the position angle of the ascending node is replaced by the position angle of the projection of the rotation axis of the orbit onto the plane of the sky. The difference between the two position angles is exactly 90°.
times, even if they form in small ensembles of only three to five stars (e.g. Sterzik & Durisen[1998]). These interactions can lead to catastrophic changes in binary orbits and even to the ejection of stars. The four stars in the GG Tau system would be enough to cause such events, unless they are in a stable configuration. Unfortunately, we have no kinematic information about the orbit of GG Tau B, which is not surprising, since we expect an orbital period on the order of 40000 years (based on the projected separation of 1400 AU). It is conceivable that GG Tau has recently changed recently, although any effect that can change the orbit of GG Tau A should also have an effect on the circumbinary disk, making it highly unlikely that the disk could maintain the planar structure we see.

On the other hand, the orbital elements derived from the astrometric data have rather large uncertainties. For example, the 1σ confidence interval for the inclination of the orbit with $a \approx 85$ AU ranges from 115° to 158° (based on $\chi^2$ as function of inclination). The errors of the angle between orbit and disk should be comparable, although not identical, since the angle between orbit and disk also depends on the orientation of the line of nodes.

In summary, we do not have the final answer about the relation between the orbit of GG Tau A and its circumbinary disk. An orbit coplanar with the disk could only cause the inner gap of the disk if the errors of the astrometric measurements are much larger than estimated. An orbit inclined to the plane of the disk would be compatible with both the astrometric data and the disk gap, but it should cause visible distortions in the disk structure. An explanation for the fact that no distortions in the disk have been detected could be that the orbit GG Tau A has only been changed recently, although any effect that can change the orbit of the stars should also disturb the structure of the disk. On the other hand, we should not forget the possibility that the gap in the disk is not related to GG Tau Ab, but some hitherto unknown companion. However, another companion would be pure speculation.

The most likely explanation seems to be a combination of slightly underestimated astrometric errors and a (small) misalignment between the planes of the orbit and the circumbinary disk. More observations over a larger section of the binary orbit are needed.

Acknowledgements. I thank the referee Herve Beust for his comments and suggestions that helped to improve the paper.

References

Artymowicz, P. & Lubow, S. H. 1994, ApJ, 421, 651
Beust, H. & Dutrey, A. 2005, A&A, 439, 585
Beust, H. & Dutrey, A. 2006, A&A, 446, 137
Diolaiti, E., Bendinelli, O., Bonaccini, D., et al. 2000, A&AS, 147, 335
 Duchêne, G., McCabe, C., Ghez, A. M., & Macintosh, B. A. 2004, ApJ, 606, 969
Elias, J. H. 1978, ApJ, 224, 857
Ghez, A. M., Weinberger, A. J., Neugebauer, G., Matthews, K., & McCarthy, Jr., D. W. 1995, AJ, 110, 753
Ghez, A. M., White, R. J., & Simon, M. 1997, ApJ, 490, 353
Guilloteau, S., Dutrey, A., & Simon, M. 1999, A&A, 348, 570
Hartigan, P. & Kenyon, S. J. 2003, ApJ, 583, 334
Hilditch, R. W. 2001, An Introduction to Close Binary Stars (Cambridge, UK: Cambridge University Press)
Krist, J. E., Stapelfeldt, K. R., & Watson, A. M. 2002, ApJ, 570, 785
Leinert, C., Zinnecker, H., Weitzel, N., et al. 1993, A&A, 278, 129
Lenzen, R., Hartung, M., Brandner, W., et al. 2003, in Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, ed. M. Iye & A. F. M. Moorwood, SPIE Proceedings No. 4841, 944–952
McCabe, C., Duchêne, G., & Ghez, A. M. 2002, ApJ, 575, 974
McCaughrean, M. J. & Stauffer, J. R. 1994, AJ, 108, 1382
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in C, 2nd edn. (Cambridge, UK: Cambridge University Press)
Roddier, C., Roddier, F., Northcott, M. J., Graves, J. E., & Jim, K. 1996, ApJ, 463, 326
Rousset, G., Lacombe, F., Puget, P., et al. 2003, in Adaptive Optical System Technologies II, ed. P. L. Wizinowich & D. Bonaccini, SPIE Proceedings No. 4839, 140–149
Sterzik, M. F. & Durisen, R. H. 1998, A&A, 339, 95
Tamazian, V. S., Docobo, J. A., White, R. J., & Woitas, J. 2002, ApJ, 578, 925
White, R. J. & Ghez, A. M. 2001, ApJ, 556, 265
Woitas, J., Kohler, R., & Leinert, C. 2001, A&A, 369, 249

Table 3. Parameters of the best orbital solutions.

| Orbital Element | Orbit coplanar with disk | Orbit not coplanar w. disk | most plausible orbit (see Sect. 4) |
|-----------------|-------------------------|---------------------------|----------------------------------|
| Date of periastron $T_\text{p}$ | 2477680 +4500/−2700 (July 2071) | 2460050 +4300/−500 (April 2023) | 2463400 +1470/−5420 (June 2032) |
| Period $P$ (years) | 162 ±15 | 1400 ±1700/−1300 | 403 ±67 |
| Semi-major axis $a$ (mas) | 243 +58/−10 | 977 +96/−96 | 429 |
| Semi-major axis $a$ (AU) | 34 ±2.8 | 137 ±17/−16 | 60 |
| Eccentricity $e$ | 0.26 ±0.05 | 0.75 ±0.03/−0.03 | 0.44 ±0.02/−0.03 |
| Argument of periastron $\omega$ (°) | 91 ±13 | 8 ±9 | 19 ±10 |
| P.A. of ascending node $\Omega$ (°) | 277 ±2.0 | 318 ±19/−7 | 131 ±13 |
| Inclination $i$ (°) | 143 ±13 | 128 ±7/−4 | 132.5 ±1.9 |
| Angle between orbit and disk | 0.02 ±1.9 | 31.8 ±1.5 | 24.9 ±1.7 |