

LETTER TO THE EDITOR

# First astronomical unit scale image of the GW Orionis triple system

## Direct detection of a new stellar companion

J.-P. Berger<sup>1,2</sup>, J. D. Monnier<sup>3</sup>, R. Millan-Gabet<sup>4</sup>, S. Renard<sup>2</sup>, E. Pedretti<sup>5</sup>, W. Traub<sup>6</sup>, C. Bechet<sup>13</sup>, M. Benisty<sup>7</sup>,  
N. Carleton<sup>8</sup>, P. Huguenaier<sup>1</sup>, P. Kern<sup>2</sup>, P. Labeye<sup>9</sup>, F. Longa<sup>2</sup>, M. Lacasse<sup>8</sup>, F. Malbet<sup>2</sup>, K. Perraut<sup>2</sup>,  
S. Ragland<sup>10</sup>, P. Schloerb<sup>11</sup>, P. A. Schuller<sup>12</sup>, and E. Thiébaud<sup>13</sup>

<sup>1</sup> European Southern Observatory, Alonso de Cordova 3107 Vitacura, Casilla 19001, Santiago de Chile 19, Chile  
e-mail: jpberger@eso.org

<sup>2</sup> IPAG, CNRS/UMR 5571, Université J. Fourier, BP-53, 38041 Grenoble Cedex, France

<sup>3</sup> University of Michigan, 941 Dennison Building, 500 Church Street, Ann Arbor, MI 48109-1090.e, USA

<sup>4</sup> California Institute of Technology, 770 S. Wilson Ave. MS 100-22 Pasadena, CA 91125, USA

<sup>5</sup> University of St. Andrews, Scotland, UK

<sup>6</sup> JPL, California Institute of Technology, M/S 301-355, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

<sup>7</sup> INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy

<sup>8</sup> Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

<sup>9</sup> CEA-DRT-LETI, 17 rue des Martyrs, 38054 Grenoble, France

<sup>10</sup> W. M. Keck Observatory, 65-1120 Mamalahoa Hwy, Kamuela, HI 96743, USA

<sup>11</sup> University of Massachusetts, Department of Astronomy, Amherst, MA 01003 4610, USA

<sup>12</sup> IAS, CNRS/UMR 8617, Université Paris-Sud, 91405 Orsay, France

<sup>13</sup> CRAL Observatoire de Lyon 9 avenue Charles André, 69561 Saint Genis Laval, France

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### ABSTRACT

**Context.** Young and close multiple systems are unique laboratories to probe the initial dynamical interactions between forming stellar systems and their dust and gas environment. Their study is a key building block to understanding the high frequency of main-sequence multiple systems. However, the number of detected spectroscopic young multiple systems that allow dynamical studies is limited. GW Orionis is one such system. It is one of the brightest young T Tauri stars and is surrounded by a massive disk.

**Aims.** Our goal is to probe the GW Orionis multiplicity at angular scales at which we can spatially resolve the orbit.

**Methods.** We used the IOTA/IONIC3 interferometer to probe the environment of GW Orionis with an astronomical unit resolution in 2003, 2004, and 2005. By measuring squared visibilities and closure phases with a good UV coverage we carry out the first image reconstruction of GW Ori from infrared long-baseline interferometry.

**Results.** We obtained the first infrared image of a T Tauri multiple system with astronomical unit resolution. We show that GW Orionis is a triple system, resolve for the first time the previously known inner pair (separation  $\rho \sim 1.4$  AU) and reveal a new more distant component (GW Ori C) with a projected separation of  $\sim 8$  AU with direct evidence of motion. Furthermore, the nearly equal (2:1) *H*-band flux ratio of the inner components suggests that either GW Ori B is undergoing a preferential accretion event that increases its disk luminosity or that the estimate of the masses has to be revisited in favour of a more equal mass-ratio system that is seen at lower inclination.

**Conclusions.** Accretion disk models of GW Ori will need to be completely reconsidered because of this outer companion C and the unexpected brightness of companion B.

**Key words.** binaries: general – stars: variables: T Tauri – Herbig Ae/Be – accretion, accretion disks – techniques: interferometric

## 1. Introduction

Stellar initial masses are controlled by the accretion of gas through disks onto the star in the protostellar phase. For a binary or multiple system this process is more complex because it potentially involves the presence of circumstellar and circumbinary gas reservoirs that control the mass distribution (Bate & Bonnell 1997; Ochi et al. 2005). Understanding the origin of such a distribution therefore requires the observation of multiple systems, the characterisations of their masses, and of the nature of the accretion sources.

GW Orionis is a single-line spectroscopic binary Classical T Tauri Star with an orbital period of 242 days located at  $\approx 400$  pc

(Mathieu et al. 1991)<sup>1</sup>. The primary star's mass has been estimated to be  $2.5 M_{\odot}$  and the secondary's as  $0.5 M_{\odot}$  with an expected separation of  $\sim 1$  AU (circular orbit of inclination  $\approx 27^{\circ}$ ). Evidence of a third companion was found based on the analysis of radial velocity residuals (confirmed period of 3850 days; Latham, priv. comm.). The spectral energy distribution (SED) of the unresolved complete system shows a large infrared excess compared with a photosphere from a 5662 K G5 star (Cohen & Kuhl 1979) with a strong 10-microns silicate emission feature. An important near-to-mid-infrared dip in the SED has been interpreted as the signature of a circumbinary (CB) disk, whose

<sup>1</sup> Distance confirmed by Sandstrom et al. (2007); Menten et al. (2007).

**Table 1.** Epochs and array configurations of the observations.

Array config.	UT Date	Min. Base. (m)	Max. Base. (m)	Calibrators (diameters)
A35B15C10	2003-11-30	16.9	36.6	HD42807 ( $0.45 \pm 0.05$ mas)
A35B15C10	2003-12-01	"	"	HD 42807
A28B10C0	2004-12-12	7.9	29.9	HD31966, HD42807
A28B10C0	2004-12-14	"	"	HD31966, HD42807
A28B05C10	2004-12-15	10.3	28.6	HD31966, HD42807
A28B05C10	2004-12-16	"	"	HD31966, HD42807
A28B05C10	2004-12-20	"	"	HD31966, HD42807
A35B15C0	2005-11-22	14.3	36.7	HD31966 ( $0.43 \pm 0.06$ mas)

**Notes.** Adopted diameter used for calibrator HD 42807 (G2V,  $V = 6.44$ ,  $H = 5.01$ ):  $0.45 \pm 0.05$  mas and for HD31966 (G5V,  $V = 6$ ,  $7$ ,  $H = 5.2$ ):  $0.43 \pm 0.06$  mas (from getcal/NexSci). Minimum and maximum projected baselines for each configuration are given as an indication.

inner part is clearing up to 3.3 AU from the star system (Mathieu et al. 1991). Artymowicz & Lubow (1994) have attempted to simulate the interaction of the CB disk with the central system. Photometric time-dimming behaviour led Shevchenko et al. (1998) to conclude that eclipses resulted from material around GW Ori B that covers the central star.

An accurate model of the disk structure is not possible without good knowledge of the stellar components of this system. We present here the first long-baseline interferometer data on GW Ori using the IOTA interferometer and successfully obtain the first reconstructed image of a T Tauri system with astronomical-unit resolution.

## 2. Observations and data reduction

IOTA was a three 45 cm siderostats interferometer, located on Mt. Hopkins Arizona and operated by Smithsonian Astrophysical Observatory (Schloerb et al. 2006). The three telescopes (A,B,C) were movable along two perpendicular axes and could occupy 17 stations offering a way to synthesize a beam with a maximum  $35 \times 15$  m aperture. This corresponds to a resolution of  $\approx 5 \times 12$  mas in the  $H$ -band. Observations took place during period 2003 November – 2005 November. Four array configurations were used to pave the UV plane. The observations were made in the  $H$  band using the IONIC3 instrument (Berger et al. 2003). IONIC3 allowed each of the three baselines to be combined separately, which provided six interferograms. Fringe patterns were temporally encoded, detected, and locked with a PICNIC detector array (Pedretti et al. 2004, 2005).

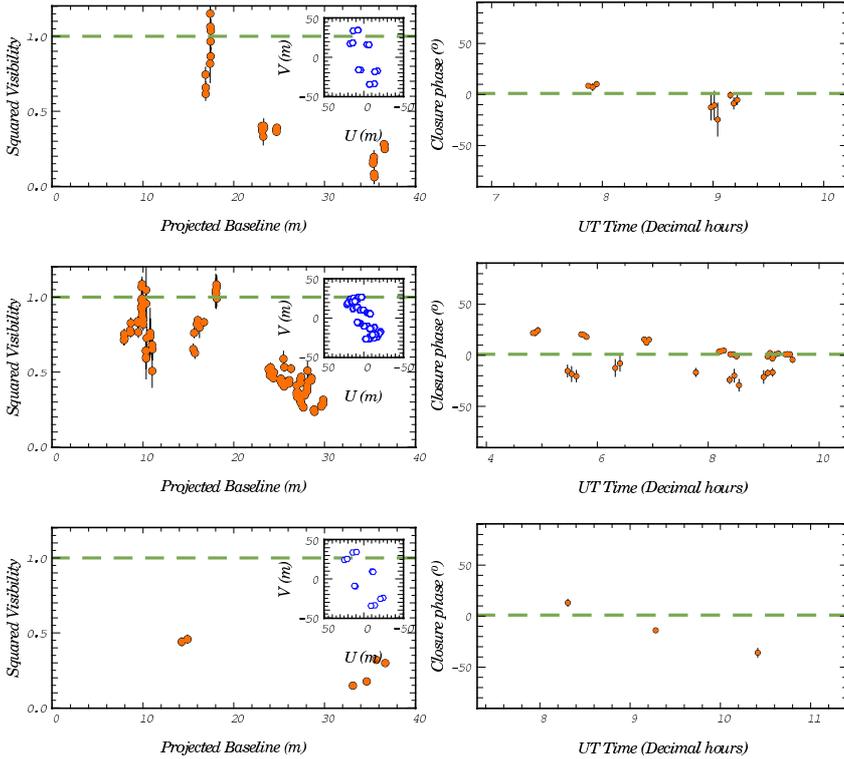
We used the data reduction method described in Monnier et al. (2004) to extract squared visibilities ( $V^2$ ) and closure phases (CP) from the interferograms. Instrumental  $V^2$  and CP effects were removed by interspersing each science target acquisition with observations of calibrators with small and known diameters. Table 1 shows a log of our observations. While the calibrators were chosen to match the brightness and spectral type of GW Ori as closely as possible to avoid instrument-induced biases, we estimated that a conservative induced CP systematic error of  $\approx 0.5^\circ$  had to be added quadratically to the statistical error computed from the set of interferograms (Monnier et al. 2006). This additional term is essentially dominated by the chromatic response of the beam combiner. Identically, our night-to-night calibration accuracy follow-up led us to adopt a conservative systematic  $V^2$  calibration error of  $\sigma_{V^2} = 0.05$  added quadratically to the statistical error on  $V^2$ . Our calibrated data set resulted in the following statistically independent measurements: 27  $V^2$  and 9 CP in 2003, 111  $V^2$  and 37 CP in 2004 and 6  $V^2$  and 3 CP measurements in 2005. The calibrated data are available from the authors in the OI-FITS format (Pauls et al. 2005).

The calibrated  $V^2$  and CP data are presented in Fig. 1. The conclusions that can be drawn from an inspection of these data include: 1) GW Orionis is clearly resolved at most of the spatial scales probed by IOTA; 2) The  $V^2$  and CP curves show an oscillation pattern typical of a multiple component system; 3) there is a clear non-zero closure phase signal at all epochs, which hints at non centro-symmetric emission. The contribution of the circumprimary disk's  $H$ -band emission to the  $V^2$  curve are most probably negligible because their expected angular size is smaller than the close binary separation, which is already underresolved by our observations. We note that the CB disk inner rim is too far away to contribute significantly to the  $H$ -band emission. This inspection combined with the already known binarity of GW Orionis and the evidence of a putative companion to the spectroscopic system (Mathieu et al. 1991 and Latham priv. comm.) has led us to focus our analysis on the search for sources of point-like emission in the data.

## 3. Modelling and results

### 3.1. Visibility and closure phase modelling

For the purpose of our fit we temporally binned the data by considering three bins, i.e. 2003 (2003-11-30 to 2003-12-01), 2004 (2004-12-12 to 2004-12-20) and 2005 (2005-11-22). These three epoch bins allowed us to neglect orbital motions within each fit (even for the longest epoch, 2004, the eight days of observations only span 3% of the orbit, and therefore the orbital motion introduces negligible errors). We first fitted simultaneously  $V^2$  and CP data with a binary model. To achieve this, we carried-out a  $\chi^2$  fine grid computation in search for the minimum. We exhaustively searched the parameter space of flux ratios ( $f$ ), component separations ( $\rho$ ), and position angles ( $\theta$ ). The resulting fits at all epochs were poor and unacceptable (reduced  $\chi^2 > 30$ ), which lead us towards a triple system model as hypothesized by Mathieu et al. (1991). All components were considered to be unresolved and the fine grid covered a range of realistic values. The fitting procedures defined all the above-mentioned parameters with respect to a reference source (A), i.e. not necessarily the primary in the usual sense of it. The fitting procedure revealed that epoch 2005, for which we had the least amount of data, allowed two equally plausible parameters for the tertiary component (C), and both solutions are included. We confirm that the triple model improves the reduced  $\chi^2$  considerably, finding 0.6, 1.6, and 0.1 for 2003, 2004, and 2005 respectively. The model parameters and associated errors can be found in Table 2. We find that the component flux ratio remains roughly constant for all epochs, which gives confidence in our identification of the components. We adopt the notation that the brightest component is referred to as "A", the other component in the close pair as



**Fig. 1.** Squared visibility as a function of the projected baseline (*left*) and closure phases as a function of UT time for the epochs 2003, 2004, and 2005 (*right*). The inset shows the corresponding UV coverage.

**Table 2.** Triple system parameters: flux ratio, separation, position angle, associated errors, and reduced  $\chi^2$  as obtained from the fitting procedure and MIRA reconstruction software.

Epoch	$f_B/f_A$	$\rho_{AB}$ (mas)	$\theta_{AB}$ (°)	$f_C/f_A$	$\rho_{AC}$ (mas)	$\theta_{AC}$ (°)	$\chi^2$
2003	$0.64 \pm 0.19$	$3.3 \pm 0.6$	$26 \pm 24$	$0.21 \pm 0.02$	$22.7 \pm 3.3$	$247 \pm 8$	0.6
2004	$0.57 \pm 0.05$	$3.4 \pm 0.8$	$189 \pm 24$	$0.24 \pm 0.02$	$18.6 \pm 1.3$	$207 \pm 10$	1.6
2005	$0.53 \pm 0.18$	$3.4 \pm 0.6$	$17 \pm 20$	$0.27 \pm 0.1$	$18.7 \pm 1.6$	$182 \pm 9$	0.1
2005		(alternative outer solution)		$0.27 \pm 0.05$	$12.2 \pm 2.4$	$152 \pm 11$	0.1
2004 (from MIRA)	0.7	3.5	171	0.32	16	217	NA

“B”, and the new outer component as “C.” We continue our discussion of these results in Sect. 4.

### 3.2. Image reconstruction

We used the MIRA software (Thiébaud 2008) to independently reconstruct an image out of the V2 and CP data. Only epoch 2004 has sufficient data for such an attempt. This model-independent image (see Fig. 2) is found to support our choice of the triple system discussed in the previous section. Furthermore, even though the procedures are different, the locations of the three components from the image are found to be consistent with the best-model predictions (see Table 2 for a comparison).

## 4. Discussion

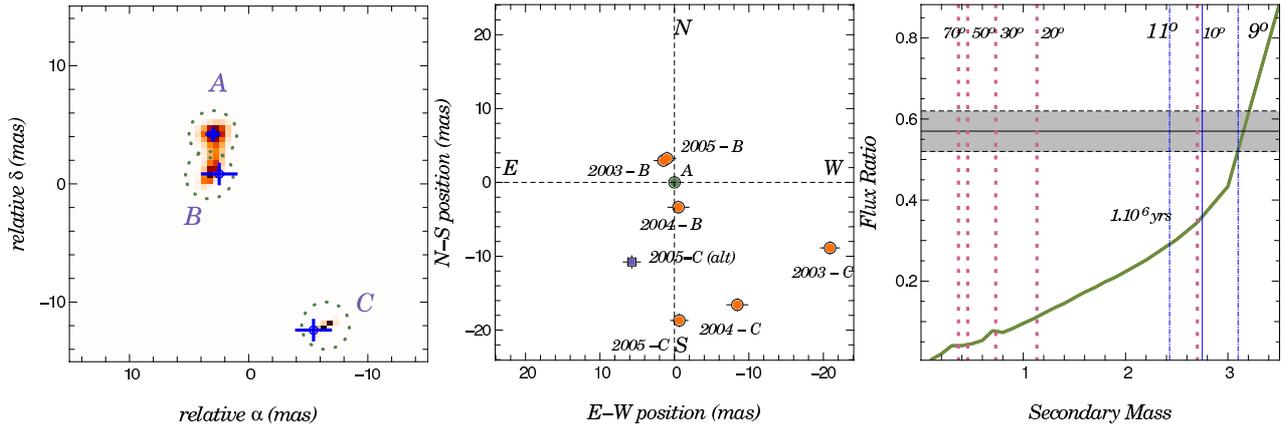
The system is resolved into three components, the spectroscopic pair (A and B) plus a new outer component (C). The inner pair shows a position reversal from 2003 to 2004 and also 2004 to 2005. This is expected since the orbital period has been measured to be  $\approx 242$  days – furthermore, our observations happen to coincide with times when the components are approximately in the plane of the sky (circular orbit phases of  $\sim 0.0, 0.6, 0.0$  in 2003, 2004, 2005 respectively). Unfortunately, this timing means that our visual orbit cannot constrain the orbital inclination. On a positive side, this means that our measured separation is close to the actual semi-major axis of the orbit,  $1.35 \pm 0.10$  AU

assuming a distance of 400 pc and knowing that the eccentricity of the orbit is  $\approx 0$  (Mathieu et al. 1991). This corresponds to a system mass of  $5.6^{+1.4}_{-1.1} M_\odot$ , somewhat higher than the previous estimate of  $3.0 M_\odot$ <sup>2</sup> (Mathieu et al. 1991).

Perhaps the most surprising aspect of this inner pair is that the *H*-band flux ratio is only about a factor of  $\sim 2$ . Previous work (e.g., Mathieu et al. 1991) had estimated that the system was composed by two stars of respectively  $2.5 M_\odot$  and  $0.5 M_\odot$  and concluded that the contribution of the secondary to the near-infrared excess was negligible.

To investigate the link between the flux ratios and the masses we used the pre-main-sequence stars theoretical evolutionary models computed by Siess et al. (2000), which were shown to be reliable enough to estimate masses with a 10% to 20% precision (Hillenbrand & White 2004). We considered, as in Mathieu et al. (1991), that the effective temperature of the primary was  $T_{\text{eff}} \approx 5700$  K and the age  $\approx 10^6$  yrs. We interpolate from the  $10^6$  yrs isochrones that this corresponds to a primary mass of  $\approx 3.6 M_\odot$ . The rightmost plot in Fig. 2 shows the expected flux ratio from the Siess et al. (2000) computation as a function of secondary mass. The straight line materializes the observed flux ratio (i.e.  $0.57 \pm 0.05$ , 2004). Additionally, we use the mass ratio

<sup>2</sup> We note that introducing the uncertainty on the distance (i.e.  $400^{+21}_{-32}$  pc) causes an error of  $\approx 20\%$  in the mass estimate which is compatible with this remark.



**Fig. 2.** *Left:* reconstructed image of the 2004 epoch using the MIRA software. Three components are resolved (encircled dots) and identified according to their brightness (A, B and C respectively from brightest to dimmest in H). Blue crosses indicate the positions as obtained from model fitting. *Centre:* presentation of the data from Table 2. Square point represents the alternative position for epoch 2005. *Right:* predicted  $H$ -band flux ratio as a function of the secondary mass with a primary mass of  $3.6 M_{\odot}$ . Shaded region is the flux-ratio constraint from our observations (epoch 2004). Vertical dashed lines provide the system inclination. Vertical blue lines are the secondary mass estimate corresponding to distance  $d \approx 414 \pm 7$  pc.

and mass function determined from radial velocity to compute the requested orbital inclination as in Mathieu et al. (1991).

If we take the most recent and precise determination of the distance by Menten et al. (2007), i.e.  $414 \pm 7$  pc, we can extract from Fig. 2 the following information:

- Our observation can be explained by a binary system with a mass ratio close to unity at low inclination and no excess from circumstellar emission. Indeed, taking the uppermost distance estimate of 421 pc the observed flux ratio in the  $H$  band can be reproduced by a system seen at low inclination ( $i \approx 9^{\circ}$ ) with a secondary mass of  $\approx 3.1 M_{\odot}$ , i.e. a mass-ratio of the order of 0.86;
- With decreasing distance the observed flux ratio requires the addition of  $H$ -band excess to the secondary and a slight increase in inclination. For example, if we take the lowest distance boundary of 407 pc, the expected secondary-to-primary ratio is  $\approx 0.29$ , which requires a secondary circumstellar excess of roughly the same value  $\approx 0.28$ . The requested inclination is then  $\approx 11^{\circ}$ .

Although this analysis is subject to important uncertainties, including the primary spectral type estimate, we tested that our conclusions hold at a qualitative level, i.e. that the *GW Ori inner system is probably seen at a much lower inclination (i.e.  $\approx 10^{\circ}$ ) with more circumsecondary  $H$  band emission than previously thought (Mathieu et al. 1991)*. Reconciling our observation with the observed eclipses by Shevchenko et al. (1998) is a puzzle we cannot solve.

Another important discovery of our work is the existence of source C. We detected C in each epoch and found clear evidence for motion with respect to the inner pair AB. We compared our motion to the preliminary 3850 day orbit recently inferred from long-term radial velocity monitoring (Latham, priv. comm.) but did not find a solution that could simultaneously fit our motions and the spectroscopic orbital elements. If the 20 mas separation of AC is the true semi-major axis, then we would expect an orbital period of  $\sim 3600$  days, which is quite close to the period seen in the RV residuals. It is far from clear if this hierarchical triple is stable. Additional interferometric monitoring of the inner pair will allow the inclination to be measured directly and the matter will be settled quantitatively in the near future.

## 5. Conclusion

We have presented the first direct detection of the CTTS GW Orionis as a triple system: both the secondary and tertiary companion are spatially resolved. Our results show that the inner stars have  $H$ -band fluxes within a factor of 2 of each other, which suggests that the exact status of the pair should be revisited. The outer companion is clearly detectable, consistent with a roughly 3500 day orbital period, in line with hints from radial velocity residuals. GW Orionis offers a unique laboratory to study the dynamical evolution of a close, young and (perhaps) hierarchical triple system and its interaction with a massive disk and envelope. Rapid progress in determining the full orbital elements of the three components is possible with current interferometers in the coming years.

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