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PLANET FORMATION IN MULTIPLE STELLAR SYSTEMS: GG TAU A

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Abstract. GG Tau is a hierarchical quadruple system of young, low-mass stars. Because of its well-studied bright circumbinary ring of dust and gas surrounding the main binary GG Tau A, it is a unique laboratory to study planet formation in the disturbed environment of binary/multiple stellar systems. We have started a large observing program of GG Tau A that combines several high-resolution instruments in a multi-wavelength approach. We have recently reported the detection of a new low-mass companion in GG Tau A that turns out to itself be a triple system. This discovery was possible thanks to the very high angular resolution of the near-IR instrument PIONIER on the VLT interferometer, and was confirmed with sub-aperture masking techniques on VLT/NaCo. The detected close binary GG Tau Ab (ρ = 0.032″, or about 5 AU) provides a natural explanation for two enigmas: the discrepancy between the dynamical mass and the spectral type estimates in GG Tau A, and the absence of dust thermal emission in the vicinity of the Ab component. GRAVITY will provide the adequate angular resolution to complete the astrometric characterization of the close binary in the next 10 years. With now 5 coeval low-mass stars, GG Tau is an ideal laboratory to calibrate stellar evolution tracks at young ages (few Myr). Beyond this peculiar system, GRAVITY also has a strong potential to study the impact of multiplicity on the existence of disks, and *in fine* on planet formation mechanisms in multiple systems.

Keywords: Stars: binaries:close ; Planetary systems: proto-planetary disks ; Techniques: high angular resolution, interfeometry

1 Planet formation in binary systems

Planet formation is a common process that can occur in different environments. Exoplanet discoveries have revealed that giant planets can form and remain in stable orbits in multiple stellar systems (e.g., the Kepler systems 16, 34, 35, Doyle et al. 2011; Welsh et al. 2012), and are found both in S-type and P-type orbits (circumstellar and circumbinary case, respectively). Since about 50 % of Sun-like stars are found in binary or multiple systems in our Galaxy (for a recent review, see Duchêne & Kraus 2013), a sizable fraction of planets may have formed in such systems. The impact of stellar host multiplicity on planet formation scenarios therefore deserves serious investigation. This has only recently been made possible with the advent of very high angular resolution instruments at both infrared (IR) and sub-millimeter wavelengths (e.g., Kraus et al. 2012; Akeson & Jensen 2014; Tang et al. 2014).

Young stars in a binary system are expected to be surrounded by two circumstellar (CS) disks, located inside their Roche lobes and an outer circumbinary ring or disk outside the outer Lindblad resonances (e.g., Artymowicz & Lubow 1994). Theory of gravitational tides predicts that the outer radius of the CS disks and the inner radius of the outer ring are set by tidal truncation induced by the central binary. Hydrodynamical simulations predict

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that the inner CS disks are not completely cutoff from the outer circumbinary disk, and that material flowing in the form of *streamers* through the central cavity may replenish the CS disks. Without external feeding, the CS disks would quickly vanish as the gas and dust accrete onto the stars, which can severely affect their potential to form planets. Recent IR studies of pre-main sequence (PMS) binaries in the Taurus molecular cloud have revealed that the disk frequency dramatically drops for stellar separations smaller than about 40 au, i.e., $\rho < 0.3''$ at the distance of the closest star forming region, 140 pc (Kraus et al. 2012). Investigating the survival of CS disks (through a direct characterization of the disk properties and of gas kinematics) in close binary systems is therefore a crucial step to quantitatively evaluate the impact of stellar multiplicity on planet formation mechanisms. This requires sub-arcsec imaging capabilities, that only long-basline interferometers (or sub-aperture masking techniques on 10 m class telescopes) can offer.

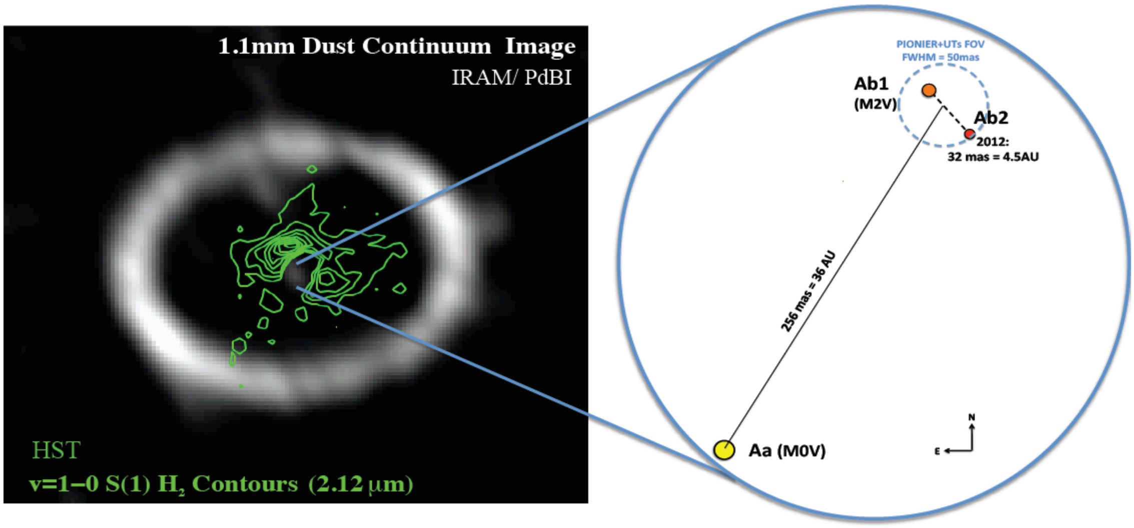

Fig. 1. Global picture of the GG Tau A triple system: **Left:** thermal emission of the outer disk/ring observed with the IRAM Plateau de Bure interferometer at 1.1 mm, from Piétu et al. (2011). The central dust emission is centered on the Aa component. **Right:** zoom on the newly identified triple system showing the derived Ab close-binary characteristics in october 2012 (adapted from Di Folco et al. 2014).

2 The emblematic multiple system GG Tau A: recent discoveries

We have recently undertaken a high-angular resolution observing program from UV to mm wavelengths of a prototypical young, low-mass, multiple stellar system: GG Tau A. Our project combines the HST, VLT/VLTI and ALMA instruments to probe the accretion and tidal mechanisms in this complex proto-planetary system. GG Tau A is one of the best-studied nearby T Tauri binaries, with a 0.26” separation (36 au on the sky plane). It stands out among young binaries because of its massive ($0.15\,M_\odot$) and bright outer ring of dust and gas which was initially discovered at mm wavelengths by Dutrey et al. (1994) and then imaged in scattered light by Roddier et al. (1996). The circumbinary disk has been resolved in thermal dust emission, and the CO gas proved to rotate at Keplerian speed (Dutrey et al. 1994; Guilloteau et al. 1999). The outer disk extends from 180 AU out to about 800 AU. One remarkable characteristics of this system is that most ($\sim 80\,\%$) of the mass is confined in an 90 au broad ring (190-280 au) which is expected to be the reservoir of material to replenish the CS disk(s). Indirect evidence for gas flow from the ring through the central cavity has been found from ^{12}CO J=2-1 gas image (Guilloteau & Dutrey 2001) and from near-IR H_2 transitions (Beck et al. 2012, tracing possible accretion shocks,). The existence of two inner CS disks is independently attested by mm emission centered on GG Tau Aa (Piétu et al. 2011), strong H_α accretion, [OI] line detection (White et al. 1999; Hartigan & Kenyon 2003), and 10μm silicate feature from hot grains in both Aa and Ab surroundings (Skemer et al. 2011).

We have recently reported the detection of a new stellar component in the GG Tau A binary system using VLTI/PIONIER instrument (Le Bouquin et al. 2011) and sub-aperture masking (SAM) techniques on the VLT/NaCo imager (Lacour et al. 2011). Thanks to the tiny 50 mas (FWHM) field of view (FOV) of VLTI+UTs in H band, we were able to separately target GG Tau Aa (M0V) and Ab (M2V) with PIONIER in H band. We

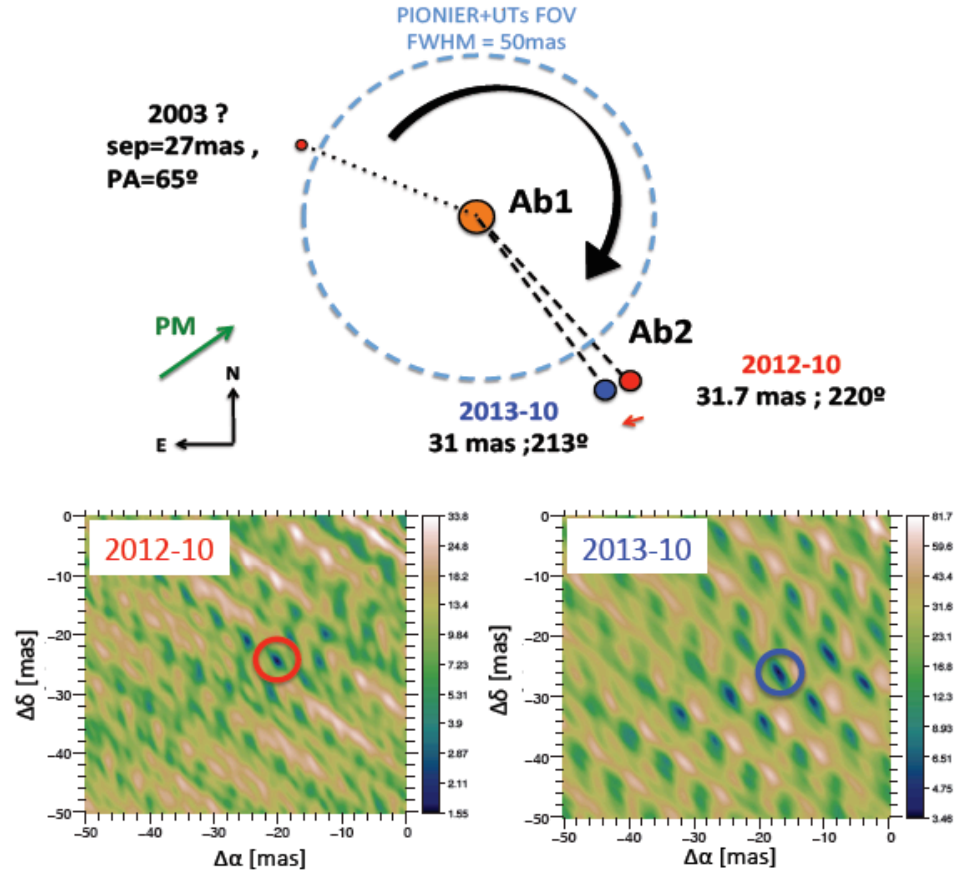

Fig. 2. Summary of GG Tau Ab close-binary astrometric measurements with VLTI/PIONIER and VLT/NaCO (2012-2013), and the tentative a posteriori identification in NaCo archival data (2003). Lower panels display the VLTI χ^2 maps that illustrate the degeneracies of the model-fitting and the impact of SNR on the close-binary identification for such faint targets ($H \sim 9$, weather conditions were much better during the 2012 observing campaign).

discovered a closure phase signal as large as 30 deg, which can be unambiguously interpreted as the signature of a companion around Ab (Di Folco et al. 2014) (see Fig. 1 for a global picture of the triple system). Its separation (32 mas) and PA (220 deg) were confirmed with NACO-SAM observations in H/Ks bands in 2012. A second epoch measurement in 2013 with PIONIER (Fig. 2) confirmed that Ab2 is a bound object that rotates in the same direction as the main binary and the outer ring (as determined by the velocity field derived from the spectro-imaging of CO gas, e.g., Guilloteau et al. 1999). From the approximate measurement of the Ab1/Ab2 flux ratio (in H, Ks and L' bands), we estimated a probable spectral type M3 for Ab2.

This new component adds $\sim 0.3\,M_\odot$ in the system, with two major consequences. First, it yields a better agreement between the stellar mass (Aa+Ab) and the dynamical mass: Hartigan & Kenyon (2003) had revised the Aa and Ab spectral types to M0 and M2 (resp.), based on an improved spectral analysis, however, it resulted in a discrepancy of $\sim 0.3\,M_\odot$ with the dynamical mass inferred from the Keplerian rotation of CO gas in the CB ring ($1.28 \pm 0.07\,M_\odot$, Guilloteau et al. 1999). Secondly, it provides a logical explanation for the lack of sub-mm/mm continuum emission around Ab attested by PdBI (Piétu et al. 2011) and ALMA observations (Dutrey et al. 2014). The new components Ab1–Ab2 are indeed surrounded by Roche lobes of radius ~ 2 AU. Tidal effects natural prevent the existence of dust disk(s) large and massive enough to be strong mm emitters (but they remain warm enough to produce the detected 10μm silicate feature).

The new stellar component was tentatively recovered from archival NaCo data, acquired in burst mode in 2003, which provides a possible third epoch observation (Fig. 2). All together, these astrometric measurements enable a preliminary fit of the orbital parameters, suggesting a (deprojected) semi-major axis $a \sim 5.6$ au, an 100 deg inclined orbit of 16 yr period, and a moderate eccentricity $e = 0.38$.

3 Potential for binary system characterization with VLTI/GRAVITY

A robust characterization of the orbital parameters definitely requires more astrometric measurements. The angular separation of the close-binary Ab1-Ab2 ($10 - 30$ mas), and the suggested orbital period make it an ideal target for the GRAVITY instrument. Few measurements during the next decade should be enough to determine the orbital parameters of the close-binary. In combination with a 0.1"-resolution mapping of the CO gas distribution in the cavity with ALMA, it should also be possible to directly probe the imprint of the binary on the accretion streamers that supply the inner circumstellar disks with fresh material from the outer ring. Although the spatial resolution of VLTI in the H and K bands remains too limited to provide an accurate determination of the CS disks characteristics around CTTS at the distance of Taurus (the disk surrounding Aa was only marginally resolved in our UTs observations, see Di Folco et al. 2014, for more details), it will be possible to take advantage of the high sensitivity of GRAVITY to observe a large set of PMS close-binary stars. Since the close-binary systems (with $\rho \lesssim 40$ AU or 0.3" at 140 pc) are key targets to investigate the impact of multiplicity on disks survival and planet formation, GRAVITY is expected to provide new constraints for a large set of PMS binary systems (through orbital characterization and IR flux ratio determination). It will in particular complement sub-aperture masking techniques that proved to be efficient in the $30 - 300$ mas range in order to study the closest systems, where the impact of multiplicity is naturally expected to be the strongest. In addition, determination of PMS binary parameters will also be essential to compare and validate the stellar evolution models especially in the $1 - 5$ Myr age range and low-mass regime ($M_\star \lesssim 0.5 M_\odot$).

4 Conclusions

This result illustrates the potential for VLTI instruments to probe the dynamics of PMS close-binary stars and the strong synergy with the sub-millimeter array ALMA to investigate the favorable physical conditions for planets to form in young, multiple stellar systems. The direct characterization of close-binary orbits with GRAVITY along the next decade can play an important role in constraining the evolution of angular momentum in complex multiple systems, and to investigate the impact of multiplicity on planet formation mechanisms.

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