GW Orionis: A pre-main-sequence triple with a warped disk and a torn-apart ring as benchmark for disk hydrodynamics

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Pre-main-sequence multiples as benchmark for disk hydrodynamics

Understanding how bodies interact with each other and with disk material holds the key to understanding the architecture of stellar systems and of planetary systems. While the interactions between point sources can be described by simple gravity, interactions with disk material require further knowledge about viscosity and gas+dust microphysics that need to be included when simulating disk-body interactions. As a result of our limited knowledge in these areas it is, for instance, still difficult to estimate the mass of a gap-opening planet from the morphology of a gap observed in a protoplanetary disk, or, to derive with certainty whether a gap is opened by a planet instead of by other processes. Furthermore, numerical simulations continue to unveil new dynamical processes that might shape protoplanetary disk structures and affect the planet populations forming from these disks. One example is *disk tearing* that might occur in the disks around multiple stars whose orbital angular momentum vectors are misaligned with respect to the rotation axis of the disk. Based on computer simulations it has been proposed in 2012 that the resulting gravitational torques could tear the disk apart and cause rings to separate from the disk and to precess independently around the central objects (Nixon et al. 2012, 2013, Facchini et al. 2013, 2018). In order to test such theories and to calibrate the fundamental parameters involved in hydrodynamic simulations, pre-main-sequence (PMS) multiple systems provide us with a unique laboratory (for general reviews on PMS binaries and multiples see for instance Dührne & Kraus 2013 and Reipurth et al. 2014). For these systems we are able to directly measure the 3-dimensional orbits and dynamical masses of the perturbing bodies and can image how the disk responds to the perturbation.

One system that has the potential to serve as such a “rosetta stone” for hydrodynamic studies, is the PMS triple GW Orionis. This system is one of the brightest and best-studied T Tauri multiple systems. It is located in the Λ Orionis star-forming region (388 pc; Kounkel et al. 2017) and has an age of ∼1 million years (Calvet et al. 2004). With orbital periods of ∼9 months and 11 years, the orbital periods and separations are just in the right range to enable a full orbit characterisation, while expecting at the same time strong interactions between the disk and the stars.

The triple star system

GW Ori is long known to be a single-lined spectroscopic binary with a 242 day period (Mathieu et al. 1991). Prato et al. (2018) reported the detection of lines associated with the secondary. Observations with the IOTA infrared interferometer resolved the inner binary and discovered a third component (Berger et al. 2011). Building on the work by Mathieu and coworkers, Czekala et al. presented in 2017 an impressive set of spectra that were obtained over 35 years with the Fred L Whipple Observatory and Oak Ridge Observatory and that provide radial velocities for the primary and secondary. Using these radial velocities and the IOTA astrometry, Czekala and colleagues derived first orbit solutions for all 3 stars. These orbit solutions indicated a 11.5 year orbit period for the tertiary and hinted at a significant misalignment between the stellar orbits and the disk, although the small orbital arc covered by the IOTA astrometry resulted in degeneracies in the orbit fits. Between 2008 and 2019, the VLT Interferometer and the CHARA array were used to monitor the astrometric orbit of the inner binary and the tertiary (Kraus et al. 2020a). The resulting orbits are shown in Figure 3 and correspond to a near-circular (e = 0.069 ± 0.009), 241.62 ± 0.05 day orbit for the inner binary and a 4216.8 ± 4.6 day orbit for the tertiary with significant eccentricity (e = 0.379 ± 0.003), where the mutual inclination between the orbital planes is 13.9 ± 1.1°.

The precise masses of the components in the GW Ori system has long been a matter of debate. Mathieu et al. (1995) estimated the mass using evolutionary tracks, yielding 2.5 M⊙ and 0.5 M⊙ for the primary and secondary, respectively. Other workers estimated the mass from the H-band flux ratio and derived more equal mass ratios (e.g.
3.2 M\(_\odot\) and 2.7 M\(_\odot\); Prato et al. 2018). These discrepancies can likely be explained by the non-negligible & time-variable contributions from circumbinary/circumtertiary dust emission biasing the near-infrared flux ratio (Kraus et al. 2020a). The dynamical masses resulting from the orbit solution are \(M_A = 2.47 \pm 0.33\), \(M_B = 1.43 \pm 0.18\), and \(M_C = 1.36 \pm 0.28\) M\(_\odot\) (Kraus et al. 2020a).

### A highly dynamical environment in the inner few au

The spectral energy distribution (SED) of GW Ori features strong excess emission from mid-infrared to millimeter wavelengths, indicating the presence of circumstellar dust. SED modeling suggested the presence of a circumbinary disk extending from around 1.2 au (Fang et al. 2017), 2.1 au (Artyomowicz & Ludow 1994) or 3.3 au (Mathieu et al. 1995) outwards. This circumbinary disk was also resolved spatially, where the VLTI and CHARA visibilities associate 16 ± 2\% of the H-band flux with circumbinary material located 2\(_\pm\_0.5\) au from the inner binary (Kraus et al. 2020a).

To fit the mid-infrared SED, Fang et al. (2014, 2017) derived a dust-depleted gap at \(\sim 45\) au. Further evidence for a truncated or gapped disk structure comes from the line profile of the CO fundamental lines, where Najita et al. (2003) noted that the line profile exhibits a narrow+broad emission component and that the line width increases towards the more energetic transitions. The system also shows signposts of active accretion, in particular Br\(\gamma\)-emission (Folha & Emerson 2001) and strong UV veiling (\(\dot{M}_{\text{acc}} = 3 \times 10^{-7}\) M\(_\odot\) yr\(^{-1}\); Calvet et al. 2004).

There has been a long debate on the viewing geometry of the system: Based on measurements of the stellar rotation period (\(P = 3.25\) days), the rotation velocity (\(v \sin i = 43.0 \pm 2.5\) km s\(^{-1}\)) and estimates of the stellar radius, Bouvier & Bertout 1989 estimated the inclination of the system to \(\sim 15^\circ\), i.e. close to face-on. Using a similar method, but other observational data, Mathieu et al. 1995 obtained an inclination of 30\(^\circ\). However, photometric observations also reported Algol-like eclipses (e.g. Shevchenko et al. 1992, Lamzin et al. 1998, Czekala et al. 2017) that have been interpreted as evidence for a nearly edge-on disk orientation.

Variability on longer time scales has been reported as well,
including dramatic changes in the near-infrared SED on timescales of \( \sim 20 \text{ yrs} \) (Fang et al. 2014). This variability might be linked with a 0.2 mag-amplitude sinusoidal variation in the V-band light curve (Czekala et al. 2017) that is phased with the orbital period of the tertiary. The origin of the long-term variability has not been answered conclusively yet, but might be due to changes in the viewing geometry or accretion rate on the circumtertiary disk.

The circumtertiary disk has been detected as submillimeter emission in the ALMA 0.02” images (Fig. 2B) and as near-infrared excess emission near the location of the tertiary in infrared interferometry data (Kraus et al. 2020a).

Misaligned rings

The intermediate/outer dust disk has been probed with JCMT (Mathieu et al. 1995) and SMA millimeter interferometry, where Fang et al. 2017 highlighted the large spatial extent (\( \sim 400 \text{ au} \)) and high mass (0.12 \( \text{M}_\odot \)) of the disk. Bi et al. 2020 and Kraus et al. 2020a acquired ALMA data with different baseline configurations and detected three dust rings. The two outer rings, R1 and R2, have radii of about 350 and 180 au and are oriented North-South and seen under intermediate inclination 37 \( \pm 1 \text{°} \) (Fig. 2A), representing the angular moment vector of the cloud that feeds the disk. The Eastern side of the disk is tilted towards us, as indicated by the strong forward-scattered light from that side of the disk (Fig. 3).

The inner submillimeter ring, R3, appears much more circular in the images – which could be interpreted as a more face-on viewing geometry. However, from extrapolating the center of the outer rings (Bi et al. 2020) and from direct imaging (Kraus et al. 2020a) it is evident that the inner ring is not centered on the position of the stars (Fig. 2B). This can be explained best if the ring is intrinsically eccentric but seen under significant inclination and appears near-circular in projection. The following additional information can be used to derive the 3-dimensional shape and orientation of the ring:

(a) Gas kinematics: \(^{12}\text{CO} \) moment 1 maps show that the rotation axis of the outer disk is oriented roughly in East-West direction (position angle 90°; e.g. Fang et al. 2017, Czekala et al. 2017) with a 'twist' in the velocity field in the inner 0.2” (Bi et al. 2020; Fig. 2 right). The twist might follow a spiral-arm pattern, with the position angle of the rotation axis changing...
Figure 3: Top-left: Overlay of the ALMA continuum image (blue) and the SPHERE scattered light image (red; credit: ESO/Exeter/Kraus et al.). Top-right: SPHERE H-band polarimetric image and model image. Bottom: Sketch of the 3-dimensional disk geometry of GW Ori. From Kraus et al. 2020a.

to 180° at 100 au and ~ 210° at ~ 30 au (Kraus et al. 2020a, Fig. 2D).

(b) Warm gas at the inner surface of the ring: The $^{12}$CO moment 0 map shows that the CO surface brightness is low at the location of the ring R3, which can be explained with the high optical depth and low gas temperature within the ring. However, there is strong CO emission near the inner edge of ring R3 on the Eastern side (labeled C1 in Fig. 2C), indicating that the Eastern side of the ring is farther away from the observer and that we see warm gas at the illuminated inner surface of the ring (Fig. 3, bottom-right; Kraus et al. 2020a).

(c) Shadows cast by the ring: SPHERE scattered light imagery (Figs. 3 and 4, top) exhibits several shadows, including narrow shadows in south-east and north-west direction (S1 and S2; Fig. 3 top) and broader shadows extending in north and south-west direction (S3 and S4). Remarkably, shadow S1 does not follow a straight line but changes direction at ~ 100 au separation (Fig. 3 top-right), indicating that the shadow falls onto a curved surface in the inner 100 au. Simultaneous modeling of the shadow morphology and of the ALMA continuum geometry yields an eccentricity $e = 0.3$ and a semi-major axis of 43 au radius for ring R3 and that the ring is seen under inclination of 155° (Fig. 3 Kraus et al. 2020a).

Broken & warped disk geometry

Shadows have been observed in several protoplanetary disks, but GW Ori is (to my knowledge) the first case where the ring casting the shadow has been spatially resolved. This enables tight constraints on the shape and 3-dimensional orientation of the misaligned ring as well as the curvature of the warped disk surface inside of the middle ring R2 ($r \lesssim 182$ au). The scattered-light morphology shows a strong East-West asymmetry, where the bright Eastern arc A3 and the fainter Western arc A4 form together an
apparent ellipse with semi-major axis of 90 au and high eccentricity ($e = 0.65$; Fig. 4). Kraus et al. (2020a) identifies this ellipse as the point where the disk breaks due to the gravitational torque from the central triple system. The bright arc A3 constitutes the side of the warped disk surface that is facing away from Earth and that appears bright in scattered light due to the direct illumination from the stars. Arc A4 corresponds to the side facing towards us, where we see only the self-shadowed outer side of the warped surface (Fig. 4). The shadows from the misaligned ring are cast onto this warped surface and appear as shadows S1 and S2, while the broad shadows S3 and S4 correspond to the regions where the break orbit crosses the plane of the outer disk, which coincides with the direction in the warp with the highest radial column density.

**Origin of the disk misalignments**

To determine the origin of the extreme disk misalignments observed in GW Ori, two teams recently presented smoothed particle hydrodynamic simulations. Bi et al. conducted SPH simulations using the ‘phantom’ code and concluded that the gravitational torque of the stars alone cannot explain the observed large misalignment between the dust ring. Instead, they propose that an undiscovered companion located between the inner and middle ring that might have broken the disk and induced the misalignments.

The ‘sphNG’ simulation presented in Kraus et al. (2020a), on the other hand, shows the disk tearing effect, where the gravitational torque of the three stars tears the disk apart into distinct rings that precess independently around the central objects. After letting the dust distribution evolve for a few thousand years, a ring breaks out of the disk plane, whose radius ($\sim 40$ au), eccentricity ($e \sim 0.2$), and extreme misalignment agree well with the observed properties of ring R3. Also, the disk breaks and a warp forms just beyond the break radius, whose dimension, geometry, and low column density agree reasonably well with the properties of the warp derived from the GW Ori observations (Fig. 5).

Both simulations adopt similar Shakura-Sunyaev viscosities ($\alpha_{SS} = 0.008 - 0.013$ for Bi et al.; 0.01-0.02 for Kraus et al.). Therefore, it appears more likely that the different outcomes might be related to the setup of the simulation. There are differences concerning the number of stars included in the simulation (2 stars in Bi et al. simulation; 3 stars in Kraus et al. simulation) and the orbit solution that is adopted for the simulation (Czekala et al. 2017 solution and Kraus et al. 2020a solution, respectively).
Figure 5: SPH model, computed with the sphNG code developed by Matthew Bate and collaborators. The simulation adopts the triple star orbits shown in Fig. 1 and an initial disk orientation that corresponds to the outer ALMA rings R1+R2. The snapshot shows the gas density after 9500 years. Panel (A) shows the column density along the line-of-sight seen from Earth; in (B) and (C) the z-axis indicates the direction towards the observer.

**Outlook**

Over the last few decades several exciting pre-main-sequence multiple systems have been found and extensively studied, including GG Tau, HD142527, HD98800, and T Tauri. GW Ori stands out with respect to the tight constraints on the full 3-dimensional orbits for all components in the system, the dynamical masses, and our knowledge on the 3-dimensional geometry of the strongly distorted disk (for a visualization of the deduced disk geometry & orbits, see the interactive 3-dimensional model in Fig. 6). Due to this unique information, the system could serve as a valuable benchmark for calibrating hydrodynamic models and fundamental parameters under well-defined conditions. This could provide the validation & refinement that is needed before applying the models to the much less-well-constrained planet formation case, where the masses and orbits of the gap-opening bodies are not known in general. The disk-tearing effect that we might witness in GW Ori in action, constitutes an important new mechanism for moving disk material onto highly oblique or retrograde orbits, even at very wide separations from the star. At the same time, the observed torn ring seems to be sufficiently massive and might be sufficiently stable for planet formation to occur, potentially giving rise to an yet-undiscovered population of circum-multiple planets on highly oblique, long-period orbits.

An important open question concerns the origin of the outermost ring in GW Ori. The high submillimeter brightness of the inner and middle ring can likely be explained by disk tearing and dust filtration processes near the disk warp region. It is unclear whether the outer-most ring can also be explained by the dynamical interplay between the central triple system and the disk, or whether dust trapping near a planet-induced density gap might be required to explain the high submillimeter surface brightness in this region.

But what caused the misalignment between the disk and the orbits in the first place? Possibilities include turbulent disk fragmentation (Offner et al. 2010), perturbation by other stars in a stellar cluster (Clarke & Pringle 1993), the capture of disk material during a stellar flyby (Clarke & Pringle 1991), or the infall of material with a different angular momentum vector from that of the gas that formed the stars initially (Bate et al. 2010, Bate 2018). To answer this question, statistical information will be of essence, both on the disk-orbit misalignment in pre-main-sequence multiples and on the orbital architecture and spin-orbit alignment in main-sequence systems. Obtaining such constraints on a large sample of stars is a key science objective for the proposed VLTI instrument BIFROST (Kraus et al. 2019, 2020b) and could offer important new insights on both the star- and planet-formation processes.

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**References:**

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Figure 6: The SFN article contains here an interactive 3-dimensional model of the disk geometry in GW Ori, as derived in Kraus et al. 2020a. Unfortunately, it was not possible to upload the graphics to arxiv – please retrieve the SFN article from http://www.ifa.hawaii.edu/users/reipurth/newsletter/newsletter333.pdf or the 3-dimensional graphics from https://www.eso.org/public/archives/releases/pdf/eso2014a.pdf.
