Planet Formation in AB Aurigae: Imaging of the Inner Gaseous Spirals Observed inside the Dust Cavity

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Abstract

We report the results of ALMA observations of a protoplanetary disk surrounding the Herbig Ae star AB Aurigae. We obtained high-resolution (0′′1; 14 au) images in 12CO J = 2 − 1 emission and in the dust continuum at the wavelength of 1.3 mm. The continuum emission is detected at the center and at the ring with a radius (r) of ∼120 au. The CO emission is dominated by two prominent spirals within the dust ring. These spirals are trailing and appear to be about 4 times brighter than their surrounding medium. Their kinematics is consistent with Keplerian rotation at an inclination of 23°. The apparent two-arm-spiral pattern is best explained by tidal disturbances created by an unseen companion located at r of 60–80 au, with dust confined in the pressure bumps created outside this companion orbit. An additional companion at r of 30 au, coinciding with the peak CO brightness and a large pitch angle of the spiral, would help to explain the overall emptiness of the cavity. Alternative mechanisms to excite the spirals are discussed. The origin of the large pitch angle detected here remains puzzling.

Key words: planet–disk interactions – protoplanetary disks – stars: individual (AB Aurigae)

1. Introduction

Recent large facilities such as ALMA, HI CIAO/SUBARU, and SPHERE/VLT have revealed complex gas and dust structures, such as large cavities, asymmetries, and spiral patterns in protoplanetary disks, thanks to their high sensitivity and resolving power. The spiral-like features, either observed in the millimeter (mm) and sub-millimeter wavelengths or in the optical and infrared (IR) scattered light, are found around, for example, HD163296 (Grady et al. 2000; Fukagawa et al. 2010), HD100546 (Grady et al. 2001; Quanz et al. 2011), HD142527 (Fukagawa et al. 2006; Christiaens et al. 2014), HD97048 (Doering et al. 2007), MWC758 (Isella et al. 2010; Grady et al. 2013; Benisty et al. 2015), HD135344B (Muto et al. 2012), Elias 2–27 (Pérez et al. 2016), and HD 141569A (Clampin et al. 2003; Perrot et al. 2016). These spirals may appear reasonably regular, asymmetric or more reminiscent of faint discontinuous disks. The origin is basically due to gravitational disturbances, either via planet–disk interactions (e.g., Zhu et al. 2015) or gravitational instabilities inside a massive disk (Kratter & Lodato 2016). The resulting structures can be very complex (Dipierro et al. 2014; Dong et al. 2015; Flock et al. 2015; Pohl et al. 2015). Nevertheless, spiral-like features are expected to reveal disturbances, such as embedded planets, which cannot be yet directly observed when the gas of the disk is not fully dissipated.

Located at 140 pc, AB Aurigae (hereafter AB Aur) is one of the closest Herbig Ae stars of the A0 spectral type Ve (2.4 ± 0.2 Ms, DeWarf et al. 2003) and it shows an extended reflection nebula at large scales (100s au). This young star is unique, because it exhibits a very small inner disk (~2–5 au) observed in near-IR (NIR) and mid-IR interferometry (di Folco et al. 2009), surrounded by a large cavity of radius ~70 au based on the CO and mm continuum observations (Pietu et al. 2005), and a CO gas and dust-rotating ring from which external spirals are observed both in the CO (Fukagawa et al. 2004) and in the mm domain (Tang et al. 2012). The inclination of the inner and outer disks slightly varies from 23° at 20 au to 29° at 100 au scales (Tang et al. 2012). The accretion rate observed for AB Aur (1.3 × 10⁻⁷ Ms yr⁻¹; García Lopez et al. 2006; Salyk et al. 2013) is still high given the estimated age of the star (about 4 Myr).

The large-scale spirals detected at optical/NIR wavelengths (Grady et al. 1999; Fukagawa et al. 2004) extend from 100 au to 500 au. The extended CO emission mapped by the IRAM array also reveals large-scale spirals. Tang et al. (2012) found that, surprisingly, the excess of CO gas along the spirals is apparently counter-rotating with respect to the gaseous disk that Tang et al. (2012) attributed to residual gas being accreted from the envelope high above the disk mid-plane. Such a scenario is also reminiscent of the asymmetric accretion suggested for some Class 0 sources by Tobin et al. (2011).

At small scales, the wide dust gap, the warped disk (change in inclination from small to large scales by about 6°–10°), and...
the asymmetric dust ring (an intensity contrast of 3 is observed inside the mm dust ring) suggest the existence of at least one undetected companion with a mass of 0.03 $M_\odot$ at a radius of 45 au (Tang et al. 2012).

Motivated by such complex structures, we obtained ALMA observing time in Cycle 3 to image at very high angular resolution ($<0.1$) the close environment of AB Aur in CO and in the mm continuum. In this paper, we report the observations (Section 2) and the results (Section 3) of these data and then discuss them with respect to recent studies and models of planet-disk interactions (Section 4). For simpler comparison with previous work, we assume a distance of 140 pc, although the GAIA DR1 release indicates 153 ± 10 pc (Gaia Collaboration et al. 2016).

2. Observations

The observations were carried out with ALMA in Cycle 3 (project “2015.1.00089.S”) with two execution blocks on 2015 November 5 and 10, respectively. The array included 45 and 46 of the 12 m antennas, respectively. The baselines ranged from 78.1 m to 15.5 km. The gain calibrator (phase) is J0512+2927, which is $3.83^\circ$ away from AB Aur and was observed with a cycle time between AB Aur and J0512+2927 of 1 minute. The bandpass calibrator was J0510+1800. The absolute flux level is referenced to J0423$-$0120 and J0510+1800 for which flux densities of 0.77 Jy and 3.42 Jy, respectively, were determined by the ALMA monitoring program. The flux calibration is expected to be accurate at the 10% level.

The calibrations were done by EA ARC using CASA 4.5. A secondary calibrator, J0518+3306, was observed every 15 minutes in order to verify the position accuracy. It lies $5.38^\circ$ eastward of AB Aur, and is $3.83^\circ$ away from the phase calibrator J0512+2927. After standard calibration, the position difference between the known coordinate and the apparent position of the secondary calibrator is $0''019$ and $0''036$ for the two execution blocks. We conclude that the absolute positioning accuracy of this experiment is limited to $\sim0''03$.

After calibration, the data were exported to the GILDAS package for further analysis. The detected central continuum peak of AB Aur at 1.3 mm is offset by ($-$5 ± 0.3, $-$10 ± 0.4) mas from the stellar location, taken from the Hipparcos reduction of van Leeuwen (2007). As this offset is of the same order as that seen for the secondary calibrator, it is likely due to the absolute position uncertainties. We assume that the continuum peak and the stellar positions are identical.

The presented data have been corrected for the proper motion with the values of (2.63, $-$24.73) mas yr$^{-1}$ given by van Leeuwen (2007), and shifted to the epoch of 2000.0 for comparison with earlier work. All the presented maps are centered on the 1.3 mm continuum peak, which is at ($\alpha$, $\delta$) = (04:55:45.85, 30:33:04.30). The maps of $^{12}$CO 2 $-$ 1 have a spectral resolution of 0.71 km s$^{-1}$ and a sensitivity of 1.60 mJy per $0''.11 \times 0''.08$ beam (4.6 K). The effective sensitivity ($1\sigma$, including dynamic range limitations) of the continuum emission is $33\mu$Jy per $0''.14$ beam (0.04 K).

3. Results

3.1. Continuum Emission

The continuum emission at 1.3 mm is detected at the 60$\sigma$ level toward the center, and is clearly detected at the dust ring (Figure 1(b)). The total detected flux density is 16.4 mJy, which is 20% of the reported flux density of 80 mJy at 1.3 mm from our previous detection with shorter baselines (Tang et al. 2012). This suggests that the missing 80% of the flux is at a scale larger than 2$''$1, which is determined by the shortest baseline of our observation. This missing flux at a scale larger than 2$''$1 corresponds to a maximum brightness of the dust ring of $\sim0.2$ mJy per $0''.14$ beam. Accounting for this missing flux, the contrast in the dust ring between the brightest regions in the South-eastern part and the rest can be as low as about 3, although Figure 1(a) displays an apparent contrast around 5.

The dust ring is consistent with a circular structure of radius $\sim120$ au, inclined at $\sim23^\circ$ with the same axis as that derived from the gas kinematics by Piétu et al. (2005), and centered on the star. More precise values of the ring parameters are actually derived from higher sensitivity, lower angular resolution observations at 0.9 mm (Y.-W. Tang et al. 2017, in preparation).

We model the central continuum peak with an elliptical disk in the visibility plane. The best-fit disk diameter is found to be $\sim11$ au. The flux density is 2.1 mJy, which is larger than the previous detected value of 1.3 mJy with the IRAM interferometer (Tang et al. 2012). The difference is at a 3$\sigma$ level when accounting for the flux calibration accuracy. Furthermore, the different spatial filtering properties of the two observations may also contribute to the measured differences, especially since the IRAM observations did not clearly separate the central continuum from the dust ring emission. We note that the total central continuum emission is about 3.4 mJy within the inner 0$''$.6 region and the emission appears extended at the level of SN ratio of 3.

The nature of the central continuum emission is unclear. There is an elongated emission at 3.3 cm that was detected with signal-to-noise ratio of 4 along PA of $\sim170^\circ$ and was suggested as free–free jet by Rodríguez et al. (2014). The total flux density of the jet is reported to be 0.8 mJy at 7 mm. Assuming a spectral index of 0.6 for the jet, this free–free emission would give 2.2 mJy at 1.3 mm within the central 1$''$. About 65% of the emission at 1.3 mm (2.1 mJy from the inner disk and 1.3 mJy from the faint emission) can come from free–free emission.

3.2. CO Gas

Previous observations of AB Aur in CO 2 $-$ 1 and 3 $-$ 2 at angular resolutions of $\sim0''$.5 $-$ 1$''$ (Piétu et al. 2005; Lin et al. 2006) revealed that most of the gas was in a large outer disk surrounding by an extended envelope (Tang et al. 2012). The disk displayed an inner radius of 45$-$77 au (Piétu et al. 2005) depending on the isotopologue being observed, although some $^{12}$CO emission was associated with the unresolved inner dust disk (Tang et al. 2012). Large-scale CO “spirals,” extending outside the dust ring into the envelope, were reported in Lin et al. (2006) and Tang et al. (2012). Their kinematics suggest that these features trace gas infalling onto the ring from well above and below the disk mid-plane (Tang et al. 2012). On the other hand, a recent analysis of the NIR images, which uses the spectral-energy-distribution fitting, argued that these large-scale spirals can be disk-related (Lomax et al. 2016). In any case, all structures reported in these earlier studies are at $r > 100$ au and beyond.

In contrast, the new high angular resolution (about 0$''$.1) and high sensitivity (noise of 4.6 K) $^{12}$CO 2 $-$ 1 images obtained with ALMA (Figure 1) reveal that most of the detected emission here is inside the dust cavity, within 90 au from the star. The $^{12}$CO 2 $-$ 1 emission at various velocities $v_{LSR}$ (i.e.,
channel maps) is shown in Figure 2. Figure 1 clearly shows that the CO gas is inside the dust ring and there is no apparent connection with the large CO disk and the extended CO spirals mentioned in the previous works. This apparent lack of connection may, however, be partly an artifact due to our uv coverage. Any extended and smooth emission larger than about $2''$ would have been filtered out. Only compact CO features, such as spirals or rings, remain detectable.

Some idea of the impact of this filtering can be obtained by comparing with the results from Tang et al. (2012), which included short spacings from the IRAM 30 m single dish map. Smoothing our data to the same angular resolution as in Tang et al. (2012) ($0''.56 \times 0''.42$) shows that we are only recovering 25% of the line flux in the $v_{\text{LSR}}$ range of 2–5 and 7–10 km s$^{-1}$. Near the systemic velocity ($v_{\text{sys}}$ of 5.85 km s$^{-1}$) in $v_{\text{LSR}}$ of 5–7 km s$^{-1}$, the missing flux problem is more severe. Given the typical brightness measured by Tang et al. (2012) of 50 K, we estimate that the measured brightness (at the velocity where the emission peaks) should be de-biased by adding about 20–30 K, as a first-order correction for missing flux.

3.2.1. General Features

The detected $^{12}$CO 2 – 1 gas emission peaks at position P1 (see Figure 1), about 30 au from the star, where the peak
brightness temperature, \( T_B \), is 70 K at \( V_{\text{LSR}} \) of 8.32 km s\(^{-1}\). At this distance, following Piétu et al. (2005), we assume CO traces gas at a temperature of 140 K. With a line width of 1 km s\(^{-1}\) and optically thin emission, the column density of CO gas is \( 10^{17} \) cm\(^{-2}\) (surface density, \( \Sigma_{\text{gas}} = 10^{-2} \) g cm\(^{-2}\)) for a \( T_B \) of 70 K, which, for a CO gas abundance of \( 10^{-4} \) with respect to \( \text{H}_2 \), gives a total gas mass of 0.03 \( M_{\odot} \) in one beam. As the CO gas emission is at least partially optically thick, this gas mass is only a lower limit. The non-detection of \( ^{13}\text{CO} \) 3–2 (3\( \sigma \) upper limit) indicates an upper limit for the mass that is 180 times larger (an abundance ratio of CO to \( ^{13}\text{CO} \) of 560, 5.4 \( M_{\odot} \)).

The integrated intensity (moment 0) map of the \( ^{13}\text{CO} \) 2 – 1 emission appears asymmetric with respect to the central star (Figure 1). The emission is patchy, especially in the fainter part, but appears to be spiral-like to the first order. We separate the CO emission into an eastern arm and a western arm for further analysis. The total gas mass of the eastern and western spirals is estimated to be of the order of 1 \( M_{\odot} \) or more.

To display the radius dependence of these structures, we present in Figure 3(b) the deprojected moment 0 map (see description below) in polar coordinates \((r, \theta)\), where \( r \) is the distance from the 1.3 mm continuum peak, and \( \theta \) is the Azimuth counted eastwards from North. Both spirals appear to have a smaller \( r \) as azimuth increases, and are thus trailing given the known sense of rotation of the AB Aur disk. The eastern spiral consists of two separated structures, with the structures around an azimuth of 180° having a clearer \( r \) dependence.

We further analyze the CO emission as follows. First, the moment 0 map is deprojected with an inclination of 23°2 assuming the position angle (PA) of the disk rotation axis of –36° and is centered on the 1.3 mm continuum peak (Figure 3(a)). We then take the maximum locations of the \( ^{13}\text{CO} \) moment 0 image every 5° in \( \theta \). We first fit the eastern and western arms with logarithmic spirals in order to search for the best description. For the eastern spiral, the best-fit function is \( r(\theta) = 0.0785 \exp(-21.09) \), where \( \theta \) is in degrees, and the origin is at \(( -0.001, 0.009) \) from the continuum peak. Note that the data at \( r < 30 \) au in the eastern spiral are clearly deviating from the best-fit function. In all the figures the best-fit function of the eastern spiral is not shown at \( r < 30 \) au. For the western spiral, the best-fit function is \( r(\theta) = 0.038 \exp(-12.5\theta) \) and the origin is at the central continuum peak. The results are marked in Figure 3.

### 3.2.2. Kinematics

The highest velocities at which CO gas is detected are \( V_{\text{LSR}} \) of 0.46 and 15.47 km s\(^{-1}\) for the blueshifted and redshifted gas (see Figure 1(a)), respectively. We note that the position centroid of the emission at these high velocities is consistent (within the uncertainty) with the location of the central continuum peak detected at 1.3 mm. Because the peak locations of the high-velocity CO gas appear along the disk plane, this suggests that the high-velocity gas traces the inner CO disk in the equatorial regions.
rotation instead of the jet observed at centimeter wavelengths by Rodríguez et al. (2014).

We extracted the position–velocity plots along the best-fit spirals (Figures 3(c) and (d)). The predicted velocity due to Keplerian rotation ($v_{\text{kep}}$) is indicated in solid lines for the nominal inclination of $23.2^\circ$ derived from the dust, a stellar mass, $M_\star$, of $2.4 M_\odot$, and a PA of the rotation axis of $-36^\circ$, using the systemic velocity, $v_{\text{sys}}$, of $5.85 \text{ km s}^{-1}$ from Tang et al. (2012). There is no radial motion detected within the resolution of the reported observations ($0.11 \text{ arcsec}$ spectral resolution).

### 3.3. Comparison of ALMA Observations with the Optical/NIR Images

Within the mm dust cavity, small dust grains ($\mu$m size) have been detected in scattered light in the optical and NIR (Grady et al. 1999; Fukagawa et al. 2004). The polarized intensity (PI) image at 1.6$\mu$m by Hashimoto et al. (2011) exhibits asymmetric features as a function of azimuth. The observed scattered light emission traces warm small dust particles at the top of the disk surface. Hashimoto et al. (2011) fitted two inclined rings and one ring gap to the PI emission. However, the derived orientations of the rings and the gap deviate from each other, suggesting that the actual structures are not rings. The CO gas distribution from our new results shows structures that are similar to those seen in the PI image (see Figure 1(d)). Both trace the same spirals, but the 1.6$\mu$m features are inward from the CO structures. We note that the small$\mu$m dust particles responsible for the 1.6$\mu$m scattering should be well mixed with the gas, as observed in the case of IRS 48 by van der Marel et al. (2013). In addition, the extended CO emission is filtered out by ALMA.

### 4. Discussions

Several mechanisms can lead to spiral-like patterns. However, the AB Aur disk density is not large enough to make it gravitationally unstable on all scales (Piétu et al. 2005). The observation of spirals within the dust cavity rather points toward tidal disturbances by a compact object. We investigate here to what extent an embedded (planetary mass) object can
explain the observed structures. Such an object located inside the dust cavity may create both the observed mm cavity and spiral-like pattern (for example, Zhu et al. 2015).

In Dong et al. (2015), the adiabatic model with a 6 M\(_{\odot}\) planet orbiting at 50 au of \(M_\star \approx 1 M_\odot\) seems to produce structures similar to what we observe here in \(^{12}\)CO. Scaling to the mass of AB aur (\(M_\star \approx 2.4 M_\odot\)), the planet would need to have a mass of 14 M\(_{\oplus}\) and be located at an \(r\) of 30 au (location P1; see Section 3.2.1; Figure 1(c)), in order to create the observed features if we adopt this model.

This possibility is supported by several unusual features detected near the location of this putative inner planet at P1. First, the pitch angle of the eastern spiral becomes large near this point: large pitch angles are only obtained near the driving object in planetary-induced spirals. Second, there is a compact CO emission between velocities \(v_{\text{LSR}}\) of 9.04 and 11.18 km s\(^{-1}\) (see Figure 2) and the line width is larger than it is elsewhere, as expected for the streaming motions (gas accretion and jet at the circumplanetary disk) around the planet (see Gressel et al. 2013, for example). Finally, there is a 1.3 mm continuum emission with a flux of 110 \(\mu\)Jy/beam at the location P1. This matches the predicted flux densities of the circumplanetary disks of known planet candidates, of the order of 100 \(\mu\)Jy at 1.3 mm (Zhu et al. 2016). However, because the 3.3 cm continuum flux is 35.9 \(\mu\)Jy/beam at this position, we cannot rule out that the 1.3 mm continuum emission has a contribution from free–free emission.

However, this scenario faces some difficulties. In an analysis of the multi-epoch NIR images, Lomax et al. (2016) found no apparent rotation of the spiral patterns within the 5.8 year time span of the images. If the spiral patterns are induced by a planet or companion, this suggests that such an object is located at \(r > 47\) au. However, their first epoch data, using Stokes I only, is not sensitive to the region around P1 discussed here, so this result only applies to the other arms. Furthermore, a planet at P1 cannot simply explain the western spiral, because outward from the orbit of the driving planet, the perturbation is mostly a (usually tightly wound) one-armed spiral.

On the contrary, two-armed spirals are easily produced inside the orbit of the perturbing planet (see Fung & Dong 2015, for example). In this second scenario, another possible location of the planet, P2, is at the outer tip of the western spiral (i.e., at a PA of 180° and \(r = 80\) au). In this case, the spirals seen here are inner spirals, and the two arms are explained by a single perturber. A planet at this location can also explain the sharp inner edge of the dust ring seen at 1.3 mm, while there is still a significant amount of \(\mu\)m-sized dust particles (Hashimoto et al. 2011) within the mm dust cavity. This is consistent with the picture of dust filtration, where dust grains larger than 0.1 mm are trapped at the radius outside of the planet and only small dust grains and gas can accrete toward the inner disk (Zhu et al. 2012). This location is also far enough to be consistent with the lack of apparent rotation of the NIR spiral patterns found by Lomax et al. (2016).

The main difficulty in this scenario is its failure to explain the large pitch angle between P1 and the star location. One possibility would be that the inner disk part of the system is warped compared to the outer part. Indeed, attributing a single inclination to the AB Aur system appears challenging. The inclination angle of the dust ring is 23°, while NIR interferometric results suggest an inclination of only 20° for the inner dust disk (Eisner et al. 2004). The larger scale observations from Piétu et al. (2005) suggest higher inclinations, but fail to reproduce the expected Keplerian velocities. It appears that the variation of inclination as a function of scale cannot explain the large pitch angle.

All the spirals induced by planets in simulations appear to have limited contrast, the maximum being 2:1 in Dong et al. (2015), for example. The \(^{12}\)CO spiral is detected at about the 12\(\sigma\) level (see Figures 3(c) and (d)). Using a 3\(\sigma\) non-detection of the surroundings, the observed spirals have a contrast of 4:1, much higher than predictions. However, the missing flux (see Section 3.2) can easily bring this contrast down to 2:1. Furthermore, the models predict density contrasts, while we observe a brightness contrast in the CO \(J = 2 - 1\) line.

The simplest interpretation of the observed contrast is linked to the vertical thermal gradient in the disk and the expected CO opacity. The spirals have larger column densities, and the \(\tau = 1\) layer is reached at higher heights in the spirals. Therefore, the spirals are warmer gas and far from being dense enough to affect the local scale height. We note that from a comparison between \(^{12}\)CO and \(^{13}\)CO, Piétu et al. (2005) indicated a temperature difference of about a factor of 2 between the lower layer traced by \(^{13}\)CO and the \(^{12}\)CO surface. Additionally, the NIR opacity toward the star is much larger than the CO line opacity along our line of sight. We expect the scattered light to trace the inner side of the spiral structures, exactly as seen in Figure 1(d).

These spiral-like patterns are reminiscent of the patterns expected for planet-induced structures in disks, although the pitch angle seems relatively large (about 20° for the Western spiral). Indeed, it is difficult to fit the analytical shape prescriptions of Rafikov (2002) and Muto et al. (2012) to our measurement. For the south part of the eastern spiral, we find a planet location near 28 au at PA 180° (i.e., near the brightest spot), but the best-fit values for parameters \(h/r\) at the planet radius and \(\beta\) (the exponent of the velocity law of the sound speed) are 0.4 and 0.9, respectively. This is inconsistent with the measured radial temperature profile and expected thickness of our disk, as derived from hydrostatic equilibrium. The Western spiral analysis leads to similar difficulties, although a solution with a planet near 20 au is possible, assuming \(\beta = 0\).

Another exciting mechanism of the spiral wave was suggested by Montesinos et al. (2016), where shadows cast by a tilted inner disk onto the outer disk cause a drop in illumination and thus lower temperature locally. The pressure imbalance further causes a density enhancement. As suggested, this mechanism could create spiral waves with an opening angle 10°–15° in the outer disk. We note that the CO spirals detected here are within the cavity. Furthermore, there is no evidence for strong tilt of the inner (few au) disk of AB Aur compared to the observed spirals, so this mechanism is unlikely to apply to our case.

Spiral patterns can also develop under external disturbances, like asymmetric accretion (Hennebelle et al. 2017, 2016). Again, these studies assume a centrally condensed disk, different from the spirals detected here within the dust ring. Indeed, for AB Aur, accretion from the outer envelope was invoked by Tang et al. (2012) to explain the apparent counter-rotation of the gas in the outer (150–400 au) spirals. However, the opening angle of the induced spiral pattern is expected to be on the order of \(h/r\) in the Hennebelle et al. (2016) model, again much smaller than our 0.3 radian value.
Thus, while our trailing spirals are highly suggestive of disturbances due to planet–disk interaction or external disturbances, their pitch angle seems difficult to explain. We point out, however, that this apparent opening angle is only defined through a relatively limited range of azimuth (less than 180°). Furthermore, it may be affected by differential filtering of the extended emission at various velocities (see Section 3.2), especially near \( v_{\text{sys}} \), where the missing flux is largest. The effect of missing flux on the morphology of the detected spirals can be studied by combining new ALMA observations with shorter baselines covering the size-scale of the spirals.

In summary, we report the detection of gaseous spirals within a dust gap for the first time in the transitional disk AB Aur. In contrast to previous detections of the spirals in continuum emission, we are able to probe the kinematics of the spirals, which is mainly Keplerian. We argue that the spirals are most likely triggered by embedded object at two possible locations, either at 60–80 au and/or at around 30 au from the star.

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Facility: ALMA.

References

Benisty, M., Juhasz, A., Boccaletti, A., et al. 2015, A&A, 578, L6
Christiaens, V., Casassus, S., Perez, S., van der Plas, G., & Ménard, F. 2014, ApJL, 785, L12
Clampin, M., Atkinson, C., Feinberg, L., et al. 2003, AJ, 126, 385
DeWarf, L. E., Sepinsky, J. F., Guinan, E. F., Ribas, I., & Nadalin, I. 2003, ApJ, 590, 357
di Folco, E., Dutrey, A., Cheneau, O., et al. 2009, A&A, 500, 1065
Dipierro, G., Lodato, G., Testi, L., & de Gregorio Monsalvo, I. 2014, MNRAS, 444, 1419
Doering, R. L., Meixner, M., Hohlfelsz, S. T., et al. 2007, AJ, 133, 2122
Dong, R., Zhu, Z., Rafikov, R. R., & Stone, J. M. 2015, ApJL, 809, L5
Eissner, J. A., Lane, B. F., Hillenbrand, L. A., Akeson, R. L., & Sargent, A. I. 2004, ApJ, 613, 1049
Flock, M., Ruge, J. P., Dryurkevich, N., et al. 2015, A&A, 574, A68
Fukagawa, M., Hayashi, M., Tamura, M., et al. 2004, ApJL, 605, L53
Fukagawa, M., Tamura, M., Itoh, Y., et al. 2006, ApJL, 636, L153
Fukagawa, M., Tamura, M., Itoh, Y., et al. 2010, PASJ, 62, 347
Fung, J., & Dong, R. 2015, ApJL, 815, L21
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, A&A, 595, 2
Garcia Lopez, R., Natta, A., Testi, L., & Habart, E. 2006, A&A, 459, 837
Grady, C. A., Woodgate, B., Bruhweiler, F. C., et al. 1999, ApJL, 523, L151
Grady, C. A., Devine, D., Woodgate, B., et al. 2000, ApJ, 544, 895
Grady, C. A., Polomski, E. F., Henning, Th., et al. 2001, AJ, 122, 3396
Grady, C. A., Muto, T., Hashimoto, J., et al. 2013, ApJ, 762, 48
Gressel, O., Nelson, R. P., Turner, N. J., & Ziegler, U. 2013, ApJ, 779, 59
Hashimoto, J., Tamura, M., Muto, T., et al. 2011, ApJL, 729, L17
Hennebelle, P., Lesur, G., & Fromang, S. 2016, A&A, 590, A22
Hennebelle, P., Lesur, G., & Fromang, S. 2017, A&A, 599, 86
Isella, A., Carpenter, J. M., & Sargent, A. I. 2010, ApJ, 714, 1746
Kratter, K., & Lodato, G. 2016, ARA&A, 54, 271
Lin, S.-Y., Ohashi, N., Lim, J., et al. 2006, ApJ, 645, 1297
Lomax, J. R., Wisniewski, J. P., Grady, C. A., et al. 2016, ApJL, 828, L8
Montesinos, M., Perez, S., Casassus, S., et al. 2016, ApJL, 823, L8
Muto, T., Grady, C. A., Hashimoto, J., et al. 2012, ApJL, 748, L22
Pérez, L. M., Jofre, M., Martinez, P., et al. 2016, Sci, 353, 1519
Perrot, C., Boccaletti, A., Pantin, E., et al. 2016, A&A, 590, L7
Pietu, V., Guilloteau, S., & Dutrey, A. 2005, A&A, 443, 945
Pohl, A., Pinilla, P., Benisty, M., et al. 2015, MNRAS, 453, 1768
Quanz, S. P., Schmid, H. M., Geissler, K., et al. 2011, ApJ, 738, 23
Rafikov, R. R. 2002, ApJ, 569, 997
Rodríguez, L. F., Zapata, L. A., Dzib, S. A., et al. 2014, ApJL, 793, L21
Salyk, C., Herczeg, G. J., Brown, J. M., et al. 2013, ApJ, 769, 21
Tang, Y.-W., Guilloteau, S., Pietu, V., et al. 2012, A&A, 547, A84
Tobin, J. J., Hartmann, L., Chiang, H.-F., et al. 2011, ApJ, 740, 45
van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2013, Sci, 340, 1199
van Leeuwen, F. 2007, A&A, 474, 653
Zhu, Z., Dong, R., Stone, J. M., & Rafikov, R. R. 2015, ApJ, 813, 88
Zhu, Z., Ju, W., & Stone, J. M. 2016, ApJ, 832, 193
Zhu, Z., Nelson, R. P., Dong, R., Espaillat, C., & Hartmann, L. 2012, ApJ, 755, 6