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LETTER TO THE EDITOR

Possible evidence of ongoing planet formation in AB Aurigae

A showcase of the SPHERE/ALMA synergy

A. Boccaletti, E. Di Folco, E. Pantin, A. Dutrey, S. Guilloteau, Y. W. Tang, V. Piétu, E. Habart, J. Milli, T. L. Beck, and A.-L. Maire

ABSTRACT

Context. Planet formation is expected to take place in the first million years of a planetary system through various processes, which remain to be tested through observations.

Aims. With the recent discovery, using ALMA, of two gaseous spiral arms inside the ~120 au cavity and connected to dusty spirals, the famous protoplanetary disk around AB Aurigae presents a strong incentive for investigating the mechanisms that lead to giant planet formation. A candidate protoplanet located inside a spiral arm has already been claimed in an earlier study based on the same ALMA data.

Methods. We used SPHERE at the Very Large Telescope to perform near-infrared high-contrast imaging of AB Aur in polarized and unpolarized light in order to study the morphology of the disk and search for signs of planet formation.

Results. SPHERE has delivered the deepest images ever obtained for AB Aur in scattered light. Among the many structures that are yet to be understood, we identified not only the inner spiral arms, but we also resolved a feature in the form of a twist in the eastern spiral pattern due to Lindblad resonances induced by disk-planet interactions (Gressel et al. 2013). While this crucial step is well constrained for these two features, we tentatively derived mass constraints for these two features.

Conclusions. The twist and its apparent orbital motion could well be the first direct evidence of a connection between a protoplanet candidate and its manifestation as a spiral imprinted in the gas and dust distributions.

Key words. stars: individual: AB Aur – protoplanetary disks – planet-disk interactions – techniques: image processing – techniques: high angular resolution

1. Introduction

Planets are believed to form in protoplanetary disks over a few million years. Images at all wavelengths exhibit a variety of structures, such as asymmetries, clumps, rings, or spirals. Most of these features, which hypothetically betray the presence of planets via gravitational or hydrodynamical effects, have been observed in disks orbiting Herbig Ae/Be stars because of their suitable brightness, particularly in the near-infrared (NIR) (see for instance Grady et al. 2001; Clampin et al. 2003; Fukagawa et al. 2006; Isella et al. 2010; Christiaens et al. 2014). Planet formation is generally favored (Zhu 2015) over instabilities in a massive self-gravitating disk (Rice et al. 2005). In the early stage of planet formation, hydrodynamical simulations indicate that the accretion process generates at the planet location an inner and outer spiral pattern due to Lindblad resonances induced by disk-planet interactions (Gressel et al. 2013). While this crucial step is well documented by theoretical works (Dong et al. 2015; Bae & Zhu 2018), observational evidence is rare and not fully conclusive.
Recently, Muro-Arena et al. (2020) identified a kinked spiral in the protoplanetary disk SR 21, suggesting that it may be a promising system for potentially witnessing ongoing planet formation.

With a spectral type A0 (2.4 ± 0.2 $M_\odot$, DeWarf et al. 2003), AB Aurigae is one of the closest ($d = 162.9 \pm 1.5$ pc, Gaia Collaboration 2018), and one of the most intensively studied Herbig Ae star. Optical scattered light images of its protoplanetary disk have been obtained in the visible (Grady et al. 1999; Fukagawa et al. 2004), and in the NIR (Perrin et al. 2009; Hashimoto et al. 2011), revealing a moderately inclined ($i \approx 30^\circ$), flared disk and prominent spiral patterns extending from 200 to 450 au. In fact, AB Aurigae exhibits among the most spectacular spirals imaged so far in scattered light and high-contrast polarimetric imaging.

Millimetric observations have also been key in constraining the distribution of gas and dust in the AB Aur system. Using the IRAM Plateau de Bure Interferometer, Piétu et al. (2005) reported the presence of a large CO and dust rotating disk with a central cavity of an inner radius of \(\sim 70\) au. Surprisingly, Tang et al. (2012) found counter-rotating CO spirals in the outer disk, which has been explained by projection effects of accretion flows arising from above the disk’s midplane. The high accretion rate ($\sim 10^{-7} M_\odot$ yr$^{-1}$, Salyk et al. 2013) measured for this 1 Myr object reinforces this interpretation.

More recently, Tang et al. (2017) studied the CO 2-1 and dust continuum distribution at very high angular scale (0.08” or 13 au) using ALMA and revealed two spectacular CO spirals residing inside the large disk cavity. The authors speculated that these spirals are driven by planet formation and could be generated by two planets respectively located at \(\sim 30\) and 60–80 au from the star. Motivated by these results, we conducted Very Large Telescope (VLT)/SPHERE observations of the AB Aurigae system and present them in this Letter. Here, we describe the observations, analyze the data and discuss the possible origin of the inner spiral pattern.

2. Observations

AB Aur ($V = 7.05$, $H = 5.06$, $K = 4.23$) has been observed with SPHERE (Beuzit et al. 2019) in polarimetry (Dec. 2019) and in spectro-photometry (Jan. 2020). The first data set was obtained with the infrared camera IRDIS (Dohlen et al. 2008; de Boer et al. 2020) using Pupil Tracking (PT) in the $H$ band, which allows us to retrieve, at the same time, the polarized intensity of the disk and the total intensity by making use of differential polarimetric imaging (DPI) and of angular differential imaging (ADI). The second epoch used the IRDIFS-EXT mode of SPHERE, which combines IRDIS in the K1K2 filters, and the spectrograph (IFS, Claudi et al. 2008) in low-resolution mode YH ($R = 30$), also processed with ADI. The observing log is provided in Table A.1.

Both DPI and ADI increase the contrast by rejecting the starlight, exploiting either the fact that the stellar light is unpolarized or that off-axis objects rotate with the field in PT mode. While DPI provides unbiased polarimetric images of disks, ADI induces very strong photometric and astrometric artifacts owing to the self-subtraction effect (Milli et al. 2012). The data were processed at the SPHERE Data Center following Pavlov et al. (2008), Delorme et al. (2017), Maire et al. (2016). The calibrated data cubes were then processed with SpeCal for total intensity data (Galicher et al. 2018) and with a custom pipeline for polarimetric data (as in Bhowmik et al. 2019). The total intensity data were reduced with Principal Component Analysis (Soummer et al. 2012), whereas for polarimetry, we calculated the azimuthal Stokes parameters $Q$, $U$, and $V$ maps following Schmid et al. (2006). For a sanity check, we compared our polarimetric reductions with those of the IRDAP pipeline (van Holstein et al. 2020), which implements a careful treatment of the instrumental polarization. We found that since the instrumental effects are much fainter than the disk structures we further discuss below, the $Q$ images are identical in both pipelines. The first epoch is significantly better in terms of starlight rejection, therefore the following sections are mainly based on these observations.

3. Disk morphology

As the disk is moderately inclined, the ADI process strongly and irremediably attenuates the disk signal (Fig. 1c). Therefore, the following description is based on the polarimetric $H$-band $Q_\phi$ image (Figs. 1a, b). The disk is visible all across the IRDIS $11''\times 11''$ field of view. We identify three main regions: the dust ring, the outer spirals, and the inner spirals.
The position of the ring detected with ALMA in the continuum (Tang et al. 2017) is shown in Fig. 2a. In the sub-mm, it encompasses an elliptical region oriented at about 60° north to east, from a minimal radius of 0.77″ to a maximal separation of 1.19″, corresponding to a ring of ~140 au on average (yellow ellipses in Fig. 2a). The aspect ratio is consistent with an inclination of 30°. In scattered light, the ring is not homogeneous with brighter parts in the west and the northeast, as opposed to the smooth 1.3 mm image, which instead peaks to the southwest. SPHERE resolves some structures in the ring that were already reported in scattered light by Oppenheimer et al. (2008) and Hashimoto et al. (2011). In particular, a depleted region in the polarized flux, formerly reported by Oppenheimer et al. (2008), is also observed at PA = 343° although the contrast is low and its visibility is mostly a matter of intensity cut. We do not detect any point-source at this location, confirming the findings of Perrin et al. (2009).

Outward of the ring, there are several spiral-like structures which, given the sensitivity achieved with SPHERE DPI, could in fact be the trace of one single grand spiral with several ramifications. This pattern likely starts from the south and rolls clockwise while it gets broader with manifold branches (Fig. 1a). It is particularly pronounced at the east and matches well to all the spirals identified in 2009 $H$-band data by Hashimoto et al. (2011) at Subaru (orange lines in Fig. 2a), indicating no perceivable motion in ten years, as already concluded by Lomax et al. (2016) on a shorter timescale. Therefore, this pattern is unlikely to be driven by planets inside the ring. Out-of-plane CO spirals (Tang et al. 2012), which have no obvious counterpart in scattered light, are indicated in cyan (Fig. 2a).

Inward of the ring (<0.6″), we detect two main spirals (S1 and S2 in Fig. 1b), starting as close as the edge of the coronagraphic mask (about 95 mas in radius) and in good agreement with the CO spirals identified by Tang et al. (2017), and shown as green lines labeled S1_CO and S2_CO in Figs. 2b, c). The angular resolution brought by SPHERE evidences that the two inner spirals seem to intersect at the south of the star exactly at the location of an intensity peak ($\rho = 0.21″$, $PA = 177.7°$), which itself is found at a very similar position than the CO peak. S2 matches well the western CO spiral, while S1 seems to deviate from the eastern CO spiral. We suspect that this mismatch is due to the difference of angular resolution, which for ALMA is about 0.11″, while SPHERE provides in $H$ band a resolution of 0.04″. As a consequence, it is difficult to disentangle S1 from S2 at the north in the CO map. S2 is more diffuse than S1 and appears larger in the west. High-pass filtering of the polarimetric image (Fig. 2b) shows higher complexity with clumps and several arms.

While the CO map contains a cavity inward of the CO spirals the SPHERE observations reveal a third component ($PA \sim 270°$ in Fig. 1b) connecting the center of the image to S2, as a kind of “bridge” of 25–30 au long. This is not a post-processing artifact since this feature is seen both in the polarimetry image and in the total intensity ADI image, and was in fact already distinguishable in Hashimoto et al. (2011), but also in the gas line HCO$^+$ (Rivière-Marichalar et al. 2019). Whether it is a true connection or a projection effect cannot be determined with these observations alone. On each side of the “bridge”, the polarized intensity is rather low, even lower than in between the spiral arms. Interestingly, in the direction of this feature the intensity of the spiral S2 and of the ring is fainter, possibly tracing a shadow pattern. If so, it will favor a feature near the midplane of the disk. Finally, S1 shows an increase of its width at PA $\sim 115°$ as a compact clump that is ~0.12″ long (Figs. 1b and 2b), complementary images are displayed in Appendix A.

### 4. Point-like sources

Many structures are observed in the disk but two features have a strong interest. The first one ($f1$) is the strongest signal in Figs. 1b and c, south of the coronagraphic mask edge, and a second one ($f2$) is a nearly point source further out to the north. Interestingly, both show up in DPI and ADI images (Fig. 3). They are also detected at the second epoch in total intensity (ADI), but with a much lower signal to noise ratio (Fig. A.1).

We extracted the photometry and astrometry with SpeCal. The positions of the sources are based on the ADI reduction using the PCA 5 modes algorithm (Fig. 2b) and the negative fake planet injection method (for details see Galicher et al. 2018), but the values are consistent within error bars for all algorithms. $f1$ is located at $\rho = 0.160 \pm 0.006°$, $PA = 203.9 \pm 2.9°$. It coincides with the root of the eastern spiral identified as S1 in the ALMA image, where the two spirals S1 and S2 observed with SPHERE appear to intersect. The shape of this feature in the $Q_\phi$
cannot consider the total intensity contrast measurements of the other, but with a small difference in the second epoch varies from one ADI reduction to another, ranging from $6.5 \pm 0.8 \times 10^{-4}$ to $6.8 \pm 0.6 \times 10^{-4}$, depending on the effectiveness (ability to suppress the starlight) of the ADI algorithm.

Similarly, the photometry in the K1K2 IRDIS image obtained at the second epoch varies from one ADI reduction to another, but with a small difference of contrast between the two narrow band filters: $3.4 \pm 0.5 \times 10^{-4}$ and $4.3 \pm 0.5 \times 10^{-4}$, respectively. Whether it is indicative of a red color remains to be confirmed with higher quality data in the $K$ band. Overall, we cannot consider the total intensity contrast measurements of $f1$ reliable as it cannot be assimilated to a point source. On the other hand, $f2$ has a stable contrast in the $H$ band of $4.9 \pm 0.5 \times 10^{-4}$, and $4.8 \pm 0.8 \times 10^{-6}$ in K1K2, indicative of a bona-fide point source, but with a grey color. Photometric measurements with the IFS (not shown here) in the $H$ band and measured at $f1$ is quite variable from one ADI reduction to another, ranging from $6.5 \pm 0.8 \times 10^{-4}$ to $6.8 \pm 0.6 \times 10^{-4}$, depending on the effectiveness (ability to suppress the starlight) of the ADI algorithm.

The object labeled $f1$ is fitting the source of the S1 spiral which at this location features an “S” shape, suggestive of the stationary pattern composed of inward and outward spiral density waves excited by the gravitational potential of an accreting protoplanet (see Kley & Nelson 2012, for a review). The spirals are trailing, as predicted by theory, since the near side is the southeast part of the disk (Fukagawa et al. 2004) and the far side of the putative planet, whereas the flaring index has only a weak impact on the shape of the projected spiral.

To account for S1 we considered two cases for which we forced a planet to be located close to the positions of the features discussed in Sect. 4. A planet located at $r_p = 0.184''$, $\theta_p = 196.8''$ (in the orbital plane of the disk) reproduces the shape of the spiral and is also in accordance with the location of $f1$ as seen in Figs. 4a, and b (green line). The analytical model of Eq. (B.1), while simple, matches the “S” shape expected for a spiral density wave surprisingly well as it goes on to trigger the accretion of gas onto a protoplanet. On the contrary, imposing the planet location at $f2$ matches only the external part of the spiral S1 (blue line in Fig. 4a). For comparison, the contours of the CO peak in the ALMA image is shown in Fig. 4b. Being localized at the surface, the spiral twists appear slightly offset from the perturber positions (circles), which are in the midplane.

For the western spiral S2, since there is no obvious features nor strong signal which we can consider as a source, we blindly searched for the best matching model. The purple line in Fig. 4a corresponds to $r_p = 0.172''$, $\theta_p = 6.0''$. This model reproduces well the external part of the western spiral, which presents a more diffuse aspect or broader shape than the eastern one, but it fails to match the innermost, eastern arm which is less tightly wound as it approaches the occulting spot ($0.1'' < r < 0.16''$).

6. Discussions

We provide a further exploratory analysis of the two identified objects, noting that they have both been detected in polarimetry and total intensity.

The object labeled $f1$ is fitting the source of the S1 spiral which at this location features an “S” shape, suggestive of the stationary pattern composed of inward and outward spiral density waves excited by the gravitational potential of an accreting protoplanet (see Kley & Nelson 2012, for a review). The spirals are trailing, as predicted by theory, since the near side is the southeast part of the disk (Fukagawa et al. 2004) and the resolved velocity field (Piétu et al. 2005) implies that the disk is wound as it approaches the occulting spot ($0.1'' < r < 0.16''$).
signal of $f_1$ is dominated by emission. The luminosity varies as the product of the planet mass with the accretion rate, and also depends on the inner radius of the circumplanetary disk. These three parameters necessarily lead to a high degree of degeneracy. Although it is difficult to overcome the ADI bias in total intensity measured for the particular case of $f_1$, as it is not point-like, we measured a minimum contrast of $6.5 \times 10^{-4}$ in the $H$ band. If we assume a moderate accretion rate of $10^{-8} M_\odot$ yr$^{-1}$ as in Zhu (2015), it translates into a planet mass of $4 - 13 M_J$. We note that the accretion rates estimated for PDS 70b are orders of magnitude lower (Haffert et al. 2019; Hashimoto et al. 2020), which then would imply stellar mass for $f_1$. As a consequence, the flux of $f_1$ is likely not to be dominated by thermal emission.

On the contrary, the object $f_2$ is not directly associated to a spiral, so we assume its flux can be attributed to pure scattering. Mass constraints can be derived from dynamical arguments. Indeed, the inner edge of the disk cavity at $\approx 1.40$ au can be sculpted by the chaotic zone of a planetary mass object. Assuming a circular orbit for the sake of simplicity, Wisdom (1980) provides a relation between the planet/star mass ratio, and the inner edge/planet distance ratio, from which we derived a mass of $\approx 3 M_J$. The AB Aur cavity is very large, such that, if resulting from dynamical interplay with planets, several bodies including $f_1$ should be involved.

Finally, the object $f_1$ appears rotated counterclockwise from the CO peak in the ALMA image which, considering the stellar mass, the 4 yr interval, and the physical stellocentric distance of $f_1$, is in excellent agreement with the expected rotation ($14.1 \pm 1.1$° in the orbital plane) of the spiral due to the Keplerian motion of the protoplanet candidate (Fig. 4c). However, the peak of the CO emission is at a radial distance slightly larger than expected. There are a few technical reasons accounting for this difference, which remain to be investigated thoroughly. Nevertheless, to our knowledge, this is the first time that we can confidently associate the rotation of a spiral pattern with the orbital motion of a planet candidate, which reinforces our confidence in the nature of the detected spiral twist.

In conclusion, the SPHERE observations of AB Aur in scattered light combined to the ALMA data in the thermal regime provide strong evidence that we are actually witnessing ongoing planet formation revealed by its associated spiral arms. Further observations would be required to confirm this result and to derive better mass estimates for potential planets in this location.

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Table A.1. Log of SPHERE observations.

| Date UT   | Filter  | Fov rotation (°) | DIT (s) | Nexp | Texp (s) | Seeing (″) | τ₀ (ms) | Flux var (%) | TN (°) |
|-----------|---------|------------------|--------|------|---------|-----------|--------|-------------|--------|
| 2019-12-18 | IRDIS - H | 29.6             | 32     | 160  | 5120    | 0.67 ± 0.09 | 7.1 ± 0.9 | ~2         | −1.70  |
| 2020-01-17 | IRDIS - K1K2 | 38.5            | 16     | 256  | 4096    | 0.71 ± 0.22 | 5.6 ± 1.1 | ~2         | −1.77  |
| 2020-01-17 | IFS - YJH  | 38.5             | 64     | 64   | 4096    | 0.71 ± 0.22 | 5.6 ± 1.1 | ~2         | −1.77  |

Notes. The table lists (left to right columns): the date of observations in UT, the filters combination, the amount of field rotation in degrees, the individual exposure time (DIT) in seconds, the total number of exposures, the total exposure time in seconds, the DIMM seeing measured in arcseconds, the correlation time τ₀ in milliseconds, the variation of the flux during the sequence in %, and the true north (TN) offset in degrees.

Fig. A.1. Complementary images of the AB Aur system. (a) ADI image (H band) in a large field of view (10″) multiplied with the square of the stellocentric distance. (b) High-pass filtering (gradient) of the DPI image to enhance the spirals S1 and S2. (c) Second epoch ADI observations in the K1K2 filters.

Appendix A: Complementary data

Appendix B: Expression of a spiral arm

According to the theory of density waves generated by a gravitational perturber (Rafikov 2002) in protoplanetary disks, Muto et al. (2012) proposed an approximate linear relation to describe the shape of a spiral θ(r), as a function of the planet location (r_c, θ₀) and disk properties, as follows:

\[
\theta(r) = \theta_0 - \frac{\text{sgn}(r - r_c)}{h_c} \left( \frac{r}{r_c} \right) \left\{ \frac{1}{1 + \beta} - \frac{1}{1 - \alpha + \beta} \left( \frac{r}{r_c} \right)^\alpha \right\} - \left( \frac{1}{1 + \beta} - \frac{1}{1 - \alpha + \beta} \right),
\]

where h_c is the disk aspect ratio at the planet location, α and β are the power-law exponents of the angular frequency and temperature profile dependence with r. In this paper, we assumed α = 1.5 for the Keplerian velocity and β = 0.25 to account for the temperature profile which varies as r^{-2β}. This formulation is now commonly used to interpret high-contrast images in which spiral patterns are observed, but it involves a number of assumptions, in particular, the idea that small grains observed in scattered light are coupled to the gas and that a single planet induces a single spiral arm. Clearly, this is not always supported by hydro-dynamical simulations, which result in much more complex morphologies. In a more realistic situation, a planet could produce several spiral arms (Dong et al. 2015) or planet formation could inevitably lead to multiple cores and, hence, to manifold spirals (Kadam et al. 2019).