MagAO-X direct detection of an accreting protoplanet candidate in the AS209 disk

Gabriele Cugno[1], T. Thanathibodee[2], P. Calissendorff[1], M. Meyer[1], S Edwards[3], J. Bae[4], M. Benisty[5,6], E. Bergin[1], M. De Furio[1], S. Facchini[7], J. Males[8], L. Close[8] , R. Teague[9,10], O. Guyon[8,11,12], S. Haffert[8], A. Hedglen[8], M. Kautz[8] , A. Izquierdo[13,14], J. Long[8], J. Lumbres[8], A. McLeod[8], L. Pearce[8], L. Schatz[15], K. Van Gorkom[1]

[1]University of Michigan, [2]Boston University, [3]Smith College, [4]University of Florida, [5]Observatoire de la Cote d'Azur, [6]University of Grenoble Alpes, [7]Università degli Studi di Milano, [8]University of Arizona, [9]Massachussetts Institute of Technology, [10]Harvard & Smithsonian, [11]National Astronomical Observatory of Japan, [12]National Institutes of natural Sciences of Tokyo, [13]European Southern Observatory, [14]Leiden Observatory, [15]Air Force Research Laboratory

Background

AS209 is a young (1-2 Myr) star with a mass of 1.2 $M_\odot$ and is surrounded by a well-studied protoplanetary disk (DSHARP, DARTTS, MAPS). Bae et al. (2022) identified a candidate circumplanetary disk (CPD), named AS209b. The candidate is detected in 13CO within the 12CO gap at ~200au and it is associated with dynamical perturbations of the disk gas.

The presence of a CPD would likely imply that material is falling from the circumstellar disk onto the protoplanet and its CPD, producing characteristic hydrogen recombination lines, like Hα.

Conclusions

- We directly detected for the first time the outflow inferred by forbidden lines.
- The residuals show a protoplanet candidate at very high contrast. However, the candidate is not detected in the ADI reduction.
- The unknown disk extinction remains the largest challenge towards interpretation of the detected protoplanet candidate
- There is not sign of accretion at the location of AS209b
- **Follow-up observations are necessary to reveal if the candidate is real**

1 Observations and data reduction

Observations

We observed AS209 with the MagAO-X instrument, searching for localized Hα emission at the location of AS209b and at any other location in the field of view.

Data were acquired under exquisite conditions, with a seeing <0.45 arcsec for the entirety of the observing sequence, low airmass and field rotation of ~110 degrees.

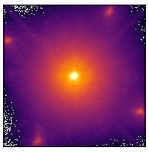


Figure 1. Combined Hα image of the AS209 dataset. Thanks to the exquisite atmospheric conditions during the observations, we estimated a Strehl ratio of ~0.4-0.45, a remarkable value at optical wavelengths.

Methods

We used spectral differential imaging (SDI), meaning that we observed simultaneously in two filters, one centered on the Hα line and the other on the nearby continuum. Being relatively cold, at optical wavelengths an accreting protoplanet only shows up in the Hα images. Hence, the continuum data can be used to model and subtract the stellar PSF. In addition, we applied angular differential imaging (ADI) to further remove the stellar contribution.

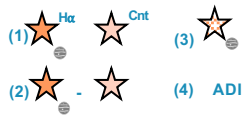


Figure 2. Schematic illustration of the SDI technique applied in this project.

2 The outflow of AS209 is imaged for the first time in our Hα data

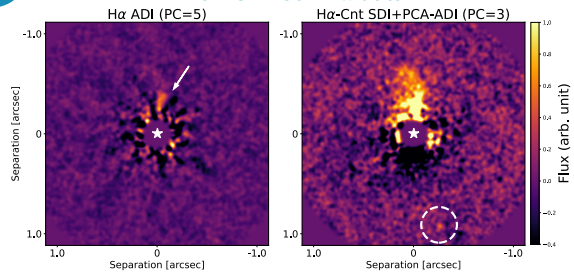


Figure 3. Left: Hα ADI residuals of AS209. The stellar PSF is removed using principal component analysis. Residuals from a jet are visible North of the star (indicated by the arrow). Right: SDI+ADI residuals of AS209. The continuum images are first scaled and subtracted, removing most of the stellar signal in the Hα images. Jet and protoplanets don't emit in the continuum, ensuring no off-axis signal is removed. The residuals confirm the detection of the jet at high significance and reveal a candidate protoplanet south of the star.

3 The outflow of AS209 is imaged for the first time in our Hα data

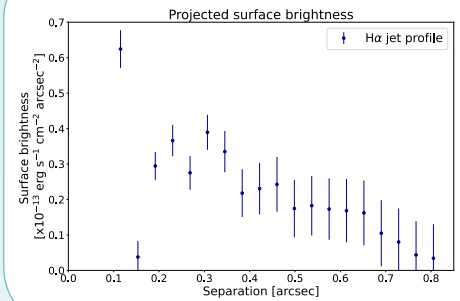


Figure 4. Surface brightness profile of the outflow from AS209. Errorbars represent the 1σ uncertainties. The first two datapoints (≤0.15 arcsec) likely suffer from PSF-subtraction artifacts. The jet appears smooth and perpendicular to the disk (see Figure 3), with an extension of 0.65 arcsec, corresponding to ~170 au when deprojected. The direct detection of the jet is consistent with the measurement of forbidden lines (like [O I]6300) from AS209 (Fang et al., 208, Banzatti et al., 2019).

4 A companion candidate is detected at large separation in the SDI reduction

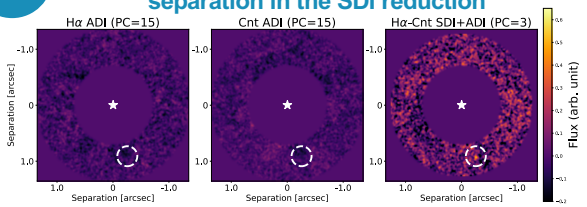


Figure 5. ADI and SDI+ADI residuals when masking the central part of the image. The data reveal a protoplanet candidate at 0.96 arcsec from the star with a contrast of ~11 mag with respect to the stellar continuum. The candidate is not detected in the individual filters, and no relevant signal is visible at that location.

5 How does the planet location compare to the structures observed in the disk?

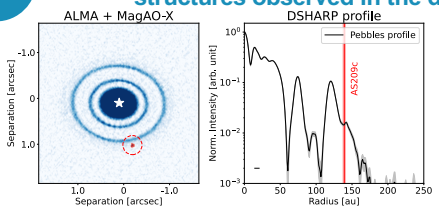
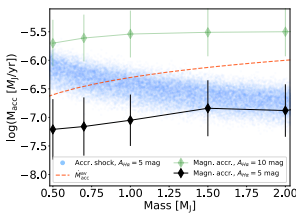


Figure 6. Location of the protoplanet candidate in the AS209 disk. *Left:* ALMA DSHARP continuum image presented in Andrews et al. (2018), combined with the MagAO-X data to highlight the location of the protoplanet with respect to the dust rings. *Right:* Radial location of the protoplanet candidate AS209c (marked in red) compared to the mm-sized dust (in black) obtained from the DSHARP survey. The spatial resolution of the profile is shown on the bottom left corner.

6 How vigorously is the protoplanet candidate accreting material?

Figure 7. Mass accretion rate of AS209c as a function of the planet mass under different scenarios. The orange dashed line represents the average mass accretion necessary to build a planet of a given mass in 2 Myr. The blue area represents the mass accretion rate estimated using the shock-heated accretion models from Aoyama et al. (2021) using the observed Hα luminosity. Black and green diamonds indicate the mass accretion rate when applying magnetospheric accretion models for $A_{Hα}$=5 mag and 10 mag respectively (Thanathibodee et al., 2019).



7 Why is the candidate not detected in the Hα ADI reduction?

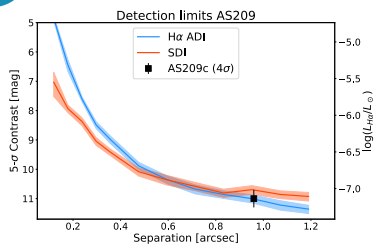


Figure 8. Hα 5σ contrast limits and Hα luminosity limits of AS209 as a function of separation. Curves obtained with the SDI technique are shown with an orange line, while curves obtained with ADI PSF-subtraction without the continuum removal are shown with a blue line. Subtracting the scaled continuum improves the contrast performance by up to 1-2~mag at short separations (≤0.4 arcsec). The detection of AS209c is reported with a black square (4σ). Shaded regions represent the systematic uncertainty due to the speckle and residuals noise.

gcugno@umich.edu

www.gcugno.github.io