A massive gas giant caught in formation

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PLANET FORMATION

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A protoplanet seen forming at some distance from its star provides evidence for planet formation via gravitational instability, a mechanism previously invoked for being responsible for the fully formed gas giant planets at large separations seen by direct imaging.

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The astronomical detection of thousands of planets in the past decade has taught us that planets are common around stars in the Galaxy. Perhaps the most basic question in the study of exoplanets is: what are the dominant mechanisms for forming planets? Some of the most challenging objects for planet formation theory are the massive gas giants that have been detected by direct imaging at large orbital separations of up to hundreds of astronomical units. Writing in *Nature Astronomy*, Thayne Currie and colleagues[1] present the exciting detection of such an object in the midst of formation: a wide separation (~100 au) sub-stellar object embedded in the disk around the young, nearby star AB Aur. The companion appears to be either a massive gas giant or a very low-mass brown dwarf. Its location can be directly connected to extended spiral features in the disk, seen in near-infrared scattered light, and the body sits inside a concentrated dust ring seen in Atacama Large Millimeter/submillimeter Array (ALMA) sub-millimetre continuum observations (Fig. 1). The appearance of the circumstellar disk, as well as the location and likely mass range of the object fit very well with models of planet formation by disk gravitational instability (GI)[2]. Therefore AB Aur b provides the most direct observational evidence yet that this formation mechanism is a viable way to form massive gas giants at separations of tens or hundreds of astronomical units.

The past few years have seen a revolution in the spatially resolved observation of circumstellar disks, revealing an ever-increasing number of extended circumstellar disks that show ring or spiral structures on spatial scales of tens or hundreds of astronomical units. These disk structures tell us that indeed it is likely that planets form at wide separations, and quickly! The famous multi-ringed disk around HL Tau[3] is located in a system that is younger than 1 Myr. In contrast to core accretion[4], GI only requires time scales of ~10,000 years to form a (proto)planet[2] and it tends to form massive objects[5]. The key to show that GI is indeed a viable formation pathway is to link the observed disk structures directly to the forming proto-planets. This is an extremely difficult task observationally. Young planets are expected to be brightest in the near and mid-infrared, but at these wavelengths there are also contributions from the disk and star. This challenge of separating planet signal from disk and star signal has meant that while several (proto)planet candidates have been directly detected in recent years (for example, in the systems LkCa 15, HD 100546, HD 169142), in none of these cases have the planets been decisively confirmed.

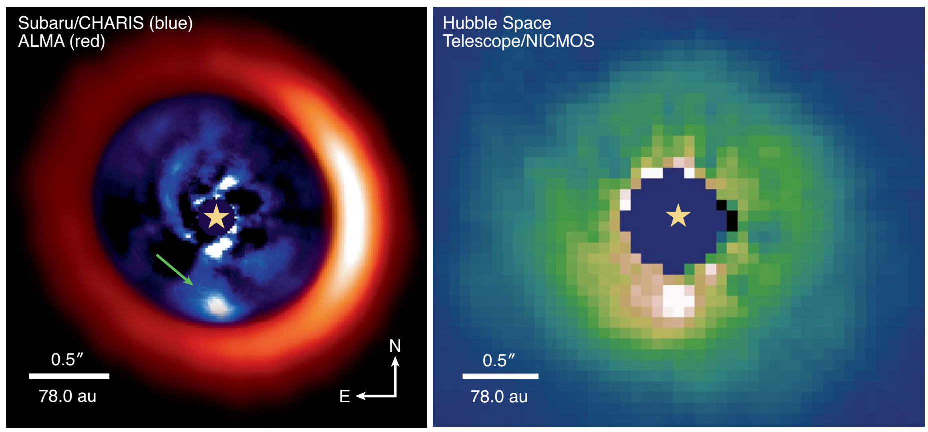

Fig. 1 | Observations of the AB Aur system. Left: a combination of near-infrared data obtained with the Subaru Telescope and sub-millimetre continuum data obtained with ALMA. The ALMA data show emission from a ring composed of large dust grains, while the Subaru data show scattered light of small dust particles as well as thermal emission from AB Aur b (marked with a green arrow). Right: Hubble Space Telescope near-infrared data obtained more than a decade before the Subaru data, shown at the same spatial scale. AB Aur b is visible as a bright blob to the south of the star. Credit: reproduced from ref. [1]., Springer Nature Ltd.

The new detection of AB Aur b stands out from these other systems, due to the abundance of evidence gathered by the author team. First, AB Aur b was detected in multiple observation epochs and using multiple data processing techniques. This rules out that it is simply an artefact or a false-positive signal. The authors then show that at the position of AB Aur b there is a drop in the degree of polarization of the scattered light signal from the circumstellar disk. This would be expected if linearly polarized scattered light from the disk mixes at this position with the unpolarized thermal emission of an embedded object. On the other hand, the degree of polarization depends on the scattering angle of the light, and therefore on the local morphology of the circumstellar disk. Thus this fact alone might not suffice to conclude that an embedded planet must be present. However, the authors also provide a meticulous spectral analysis from their data. They can show that the spectrum extracted at the position of AB Aur b deviates from the spectra extracted at several other disk locations and that the spectrum is consistent with a young high-mass gas giant, within uncertainties. The authors also detect an elevated signal at optical wavelengths, which may be expected from an embedded object that actively accretes gas (although they unfortunately fail to decisively detect Hα emission due to the optical data quality). Finally, by including archival Hubble Space Telescope data (see Fig. 1, right panel), the authors are able to detect orbital motion of AB Aur b over the course of 14 years. Their orbital fits are consistent with the expected motion of a sub-stellar object (but can unfortunately only put loose constraints on the mass, ruling out most embedded stellar companions). Taken together the observations of the authors make a compelling case for the presence of an embedded (proto)planet.

Due to the challenging nature of these observations, AB Aur is only the second system in which we can directly link observed disk structures to a (proto)planet. The first one is the PDS 70 system in which two planets were detected inside the central cavity of a ring-shaped disk[6,7]. The two systems differ significantly. While the primary star in the PDS 70 system is a K7 T Tauri star with a sub-solar mass, AB Aur is an A0 Herbig star with roughly 2.5 times the mass of the Sun. While also gas giants, the planets within the PDS 70 system reside much closer to their star (within 30 au), compared to AB Aur b, which is located at close to 100 au. Since the planets within PDS 70 have already cleared a cavity in the disk it is conceivable that they represent a slightly later evolutionary stage than AB Aur b, which is still heavily embedded.

While it is most exciting to find such strong evidence for an embedded young proto(planet), the characterization of AB Aur b is challenging. For such an object we expect that it will be surrounded by a circumplanetary disk or envelope through which gas accretes onto the (proto)planet. This was indeed recently detected for PDS 70 c[8]. This may be consistent with the finding of the author team, that the emission from AB Aur b is in fact spatially resolved, that is, the signal from the planet is more spread out than we would expect from the telescope point-spread function alone. The spectrum of AB Aur b also appears rather featureless, in particular it is missing the water absorption bands in the H-band that are typical for the atmospheres of young, massive gas giants. As the authors discuss, this may indeed indicate that the detected signal originates in the circumplanetary disk rather than from the planet itself.

Given the uncertainty where exactly the planet signal originates, the properties of AB Aur b are not yet well constrained. If it comes from the planet atmosphere and the planet is as young as 1 Myr, then the authors calculate a mass of roughly ten times that of Jupiter. However, since gravitational instability of the disk operates on very short time scales the object might be as old as the central star AB Aur, which has an age of roughly 4 Myr (ref. [9]). This may put the mass of AB Aur b up to twenty Jupiter masses, possibly making it a very low mass brown dwarf. However, if the signal originates mostly or completely from the circumplanetary disk, then extensive additional modelling work is required to estimate the mass of the central object.

Given the wide separation and its plausible mass range, AB Aur b might be the long sought-after precursor to direct imaging systems around massive stars such as κ And b (13–50 M_{Jup}, 100 au, refs. [10,11]). With the possibility of further (proto)planet candidates in the authors' data, the AB Aur system might indeed be a young counterpart to the famous HR 8799 multi-planet system[12]. ❐

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Published online: 9 May 2022
https://doi.org/10.1038/s41550-022-01665-4

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Competing interests

The author declares no competing interests.