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Signs of planet formation in protoplanetary disks

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Abstract

In this paper, I present results of four protoplanetary disks, studied by our team, that show signs of planet formation. Our high angular resolution radio interferometric observations of these sources suggest that we are witnessing different stages of the planet formation and disk evolution processes working at different scales.

1 Introduction

In the standard model ([15]) stars and planets form inside dense cores of molecular clouds. After some time, gravity becomes important and the material of the core collapses onto its center, forming a young star. At the same time, a flattened structure of dust and gas is formed around the star due to the initial rotation of the cloud. This structure, called a protoplanetary disk, plays an important role feeding material to the star and planets. To lose angular momentum, the star ejects material along its rotational axis. On timescales of 0.01 to 0.1 Myr the star produces winds and outflows that remove the material around it. About 10 Myr after the onset of collapse, the accretion and ejection of material has finished and a planetary system arises. This is the standard model for the formation of low mass stars. However, in recent years, more details have been obtained and new stages have been identified in the disk evolution corresponding to the so-called transitional disks. These disks are characterized by a deficit of dust emission in their central regions that has been attributed to a cavity. Some transitional disks show evidence at IR wavelengths of residual material close to the star, and are called pre-transitional disks, since they are thought to be in an earlier stage. Transitional disks attracted great attention since it is thought that cavities and gaps are probably created by orbiting protoplanets. Initially, transitional disks were identified through the fitting of their Spectral Energy Distributions (SEDs), but in the last years, it has been possible to image several of these cavities using large telescopes in the infrared, and interferometers in the submm and millimeter regimes. In this paper, I review some of our results on circumstellar disks that appear to be in a stage where their material starts to be removed by planet formation and/or photoevaporation.

2 The pre-transitional protoplanetary disk around HD 169142

HD 169142 is a Herbig Ae/Be star with an age of $\sim$ 10 Myr. This source has been observed from ultraviolet to centimeter wavelengths, hence its SED is well sampled and is explained by the emission of the star plus a circumstellar disk. This is one of the sources where the presence of an inner cavity and its wall were predicted based on the SED modeling ([8]). This prediction is confirmed by IR polarized light images that trace the scattered light (see Fig. 1), where a face-on disk (i= 13°) that has a radius of $\sim$ 200 au is seen ([13]). The central cavity is suggested by the decrease of emission near the inner edge of this ring (note that the central pixels in the IR image have been masked to remove the stellar emission). Besides the cavity, there is a bright ring at 30 au that has been interpreted as tracing the cavity's wall. Beyond the ring there is a gap spanning from 40 to 70 au where the observed surface brightness decreases by a factor of $\sim$3. This emission decrease likely corresponds to a drop in surface density, but given that this is a polarized light image, it is also possible that this feature could be a shadow cast by the ring. This ambiguity could be solved with an image of the dust thermal emission of the disk.

Using the Karl G. Jansky Very Large Array (VLA), we were able to get a high quality image of the dust thermal emission at 7 mm ([11], see Fig. 1) where the cavity and emission ring are clearly seen. In contrast with infrared observations, in the millimeter range a mask is not needed to attenuate the stellar emission, enabling us to reach distances very close to the central star.

As can be seen in the VLA image, the western side of the ring is brighter than the eastern one. This asymmetry in the ring is reminiscent of the lopsided structures that are expected to be produced by trapping of large dust grains, and that are considered a signpost of planet formation. The image also shows hints of the outer gap (40 - 70 au) revealed by the IR image. The inner cavity and the outer gap can be identified with a higher signal to noise ratio by obtaining an azimuthally averaged radial intensity spatial profile at 7mm (see Fig. 2, left panel). This double gapped structure may be indicating multiple and sequential planet formation in different places of HD 169142. One can also see that the ring in the IR image, which traces micron-sized dust grains, coincides in radius with the 7 mm ring, which traces the cm-sized dust grains. This is one of the few cases where the cavity's size is the same at both wavelengths, suggesting that tidal interactions with companions could have shaped the inner edge of the cavity abruptly.

We modeled the source using irradiated flared accretion disk models developed by D'Alessio ([5]). In these models the disk is heated by the star and by viscous dissipation. The vertical and radial disk's structure is determined self-consistently. D'Alessio's models also take into account vertical settling of large grains on the disk mid-plane, hence millimeter-sized grains are also included. Moreover, we have modified these models to include the effect

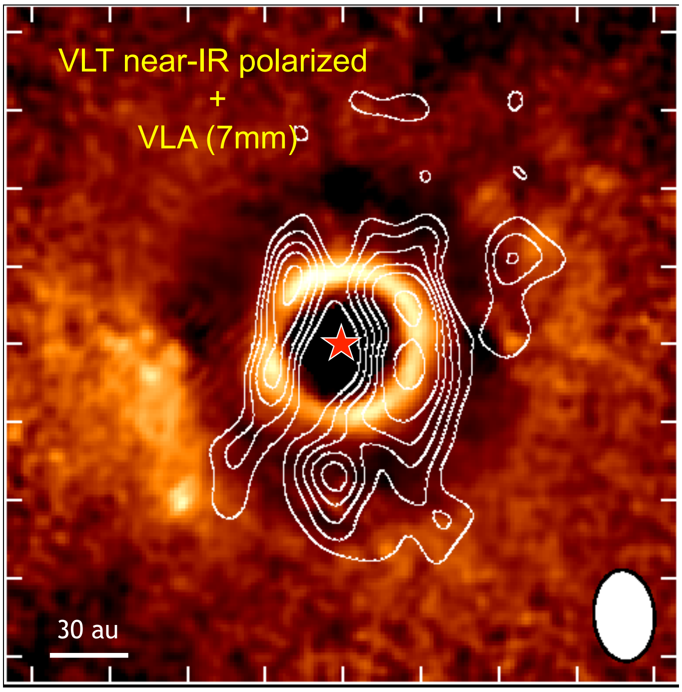

Figure 1: The HD169142 pre-transitional disk. Comparison of the 7 mm dust emission image obtained with the VLA (contours, [11]) and the IR polarized light image obtained with the VLT (color scale, [13]). The VLA beam is shown in the lower right corner.

of the cavity and annular gap by fully removing the material in these regions, but we realized that a hot component is required to reproduce the mid IR range. Therefore, we have added a small inner disk inside the cavity. Because of this residual disk, HD 169142 is actually a pre-transitional disk and the central cavity is actually a gap between the inner and outer parts of the disk (see Fig. 2, right panel). This means that this disk has two gaps, each one has a wall illuminated by the star whose contribution has also been added to the model. In the model, a large accumulation of big particles is required in the outer edges of the walls of each gap, suggesting the existence of dust refuges where planets can form. Figure 2, left panel shows the model intensity profile. The predicted image reproduces the intensity, size and shape, but it is azimuthally symmetric. This means that the observed asymmetry is not due to opacity effects caused by inclination but could be real and produced by a dust trap.

In order to search for possible protoplanet candidates, we carried out near infrared observations with the Very Large Telescope (VLT/NACO). Interestingly, an infrared point source within the inner gap was detected and interpreted as a substellar companion or planet candidate with an estimated mass of ~ 30 M_{Jup} ([14], [3]).

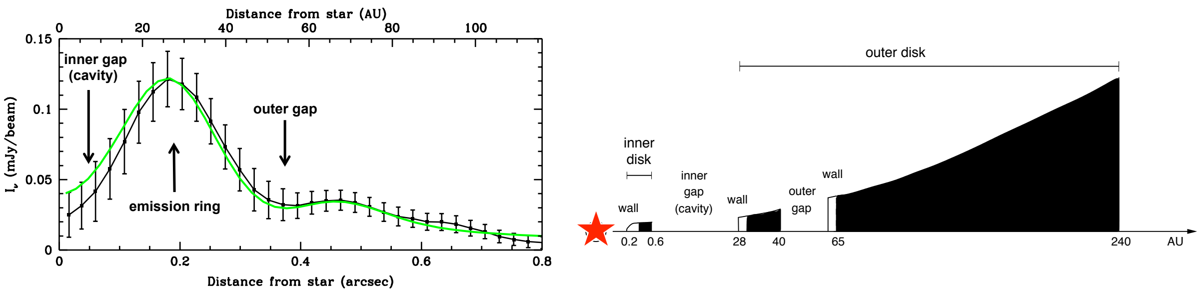

Figure 2: Left: observed (dots and black line with error bars) and modeled (green line) azimuthally averaged intensity profile of the HD 169142 disk as a function of radius. The observational data are taken from the 7 mm map shown in Figure 1. Right: A sketch of the modeled disk structure. Figures adapted from [11].

3 The protoplanetary disk of HL Tau

HL Tau is a young (∼ 2 Myr) Sun-like star still surrounded by an accretion disk and envelope. This source has been the subject of many studies after an ALMA image that revealed its dusty protoplanetary disk in great detail. It was known for a long time that this source is associated with emission originating in a circumstellar disk of ∼ 100 au in radius. In 2014, HL Tau was chosen to test the long baseline configuration of ALMA. This instrument was able to detect a large number of pairs of axisymmetric bright and dark rings in HL Tau disk ([1], see Fig. 3a). However, HL Tau is too young to host such a large number of planets that might have created these gaps. After these unexpected results, a large effort has been carried out to explain the observed structure of HL Tau disk. IR searches aimed at detecting point sources inside the multiple gaps, that could be tracing still forming planets, have been unsuccessful so far ([16]).

At wavelengths around 1 mm or smaller, the bright rings in the central region of the disk are optically thick and the possible presence of substructure in these rings cannot be established from this kind of observations. In order to study the innermost bright rings with optically thinner emission while reaching an angular resolution comparable with that of the ALMA observations, we performed VLA observations at 7 mm (see [4]). The 7 mm observations reveal that the innermost ring of HL Tau is inhomogeneous and has a massive clump of large dust grains containing a mass between 3 and 8 M_{Earth} (see Fig. 3b). We speculate that this clump may become a planet over the next millions of years and under this hypothesis we would be witnessing now in HL Tau a very early stage of the planet formation process prior to the developments of the gaps and cavity observed in transitional disks and that are attributed to tidal effect of already formed orbiting planets. It is worth noting that the young planet candidates proposed so far from infrared observations, such as that in HD 169142 ([14]; see Section 2), are found inside disk cavities or gaps, and would correspond to a latter stage. We propose that HL Tau does not host planets already formed, but its disk has undergone a fragmentation process, and the first planet embryos are being formed in the rings. Actually, already in the XVIII century when Pierre-Simon Laplace proposed

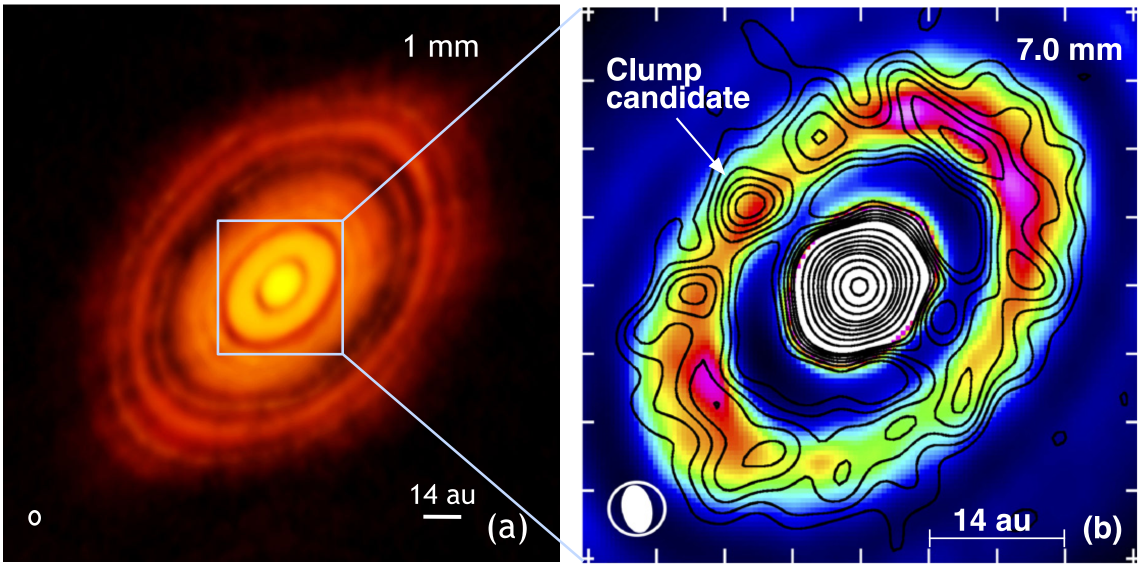

Figure 3: The HL Tau protoplanetary disk. (a) ALMA 1 mm image ([1]). (b) Overlap of the ALMA image (color scale) over the VLA 7 mm image ([4], contours). The 7mm image, which is optically thin, reveals substructure and clumping in the innermost pair of dark and bright rings. The beams are depicted in the lower left corner.

his nebular model for the formation of the Solar System, he envisioned that material will distribute in the form of annular rings where "*Condensations within each ring, all orbiting at slightly different rates, gradually accumulated to form a single planet.*" It has taken over three centuries to confirm this and it has likely been done in the HL Tau disk.

4 The dwarf pre-transitional protoplanetary disk around XZ Tau B

XZ Tau is a binary (possibly a triple) stellar system that lies about 30″ east of HL Tau (Fig. 4a). It is at the origin of an impressive sequence of outbursts that was imaged by the *HST* ([7]). In the ALMA long baseline study of HL Tau ([1]), not too much attention was paid to XZ Tau, perhaps because the observations were centered on HL Tau and the sensitivity of the instrument at $\sim$ 1 mm drops by a large factor toward XZ Tau. XZ Tau was separated into two components at 2.9 mm (Fig. 4b), but we obtained additional important information from the $\sim$ 1 mm data. We will focus on the northern component of the XZ Tau system, called XZ Tau B.

Figure 4c shows the ALMA image of XZ Tau B in the continuum at $\sim$ 1 mm, reaching an unprecedented angular resolution of $0.03'' \times 0.019''$ ([12]). The image shows an angularly resolved source with a size of $\sim$ 7 au (d = 140 pc) and centered on the position of the XZ Tau. The source shows a decrease of emission towards the center, suggesting that it traces a very

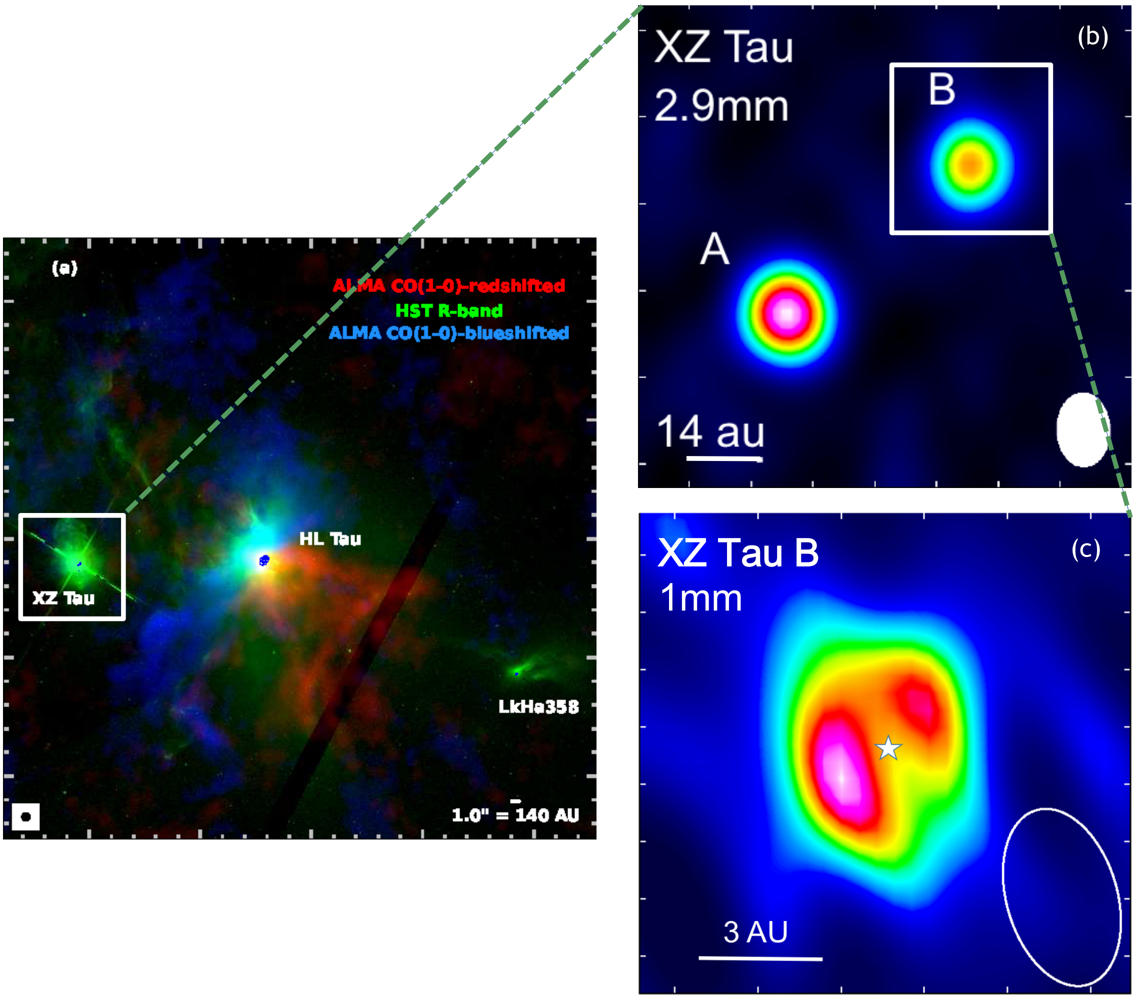

Figure 4: The HL/XZ Tau region as seen by ALMA. (a) Wide field of view image, centered on HL Tau and including the neighbor stars XZ Tau and LKHα 358. The beam is depicted in the lower left corner. (b) The XZ Tau binary system as seen by ALMA at ~ 3 mm. (c) XZ Tau B as seen by ALMA at ~ 1 mm. The beam is shown in the lower right corner. Figure adapted from [12] and [1].

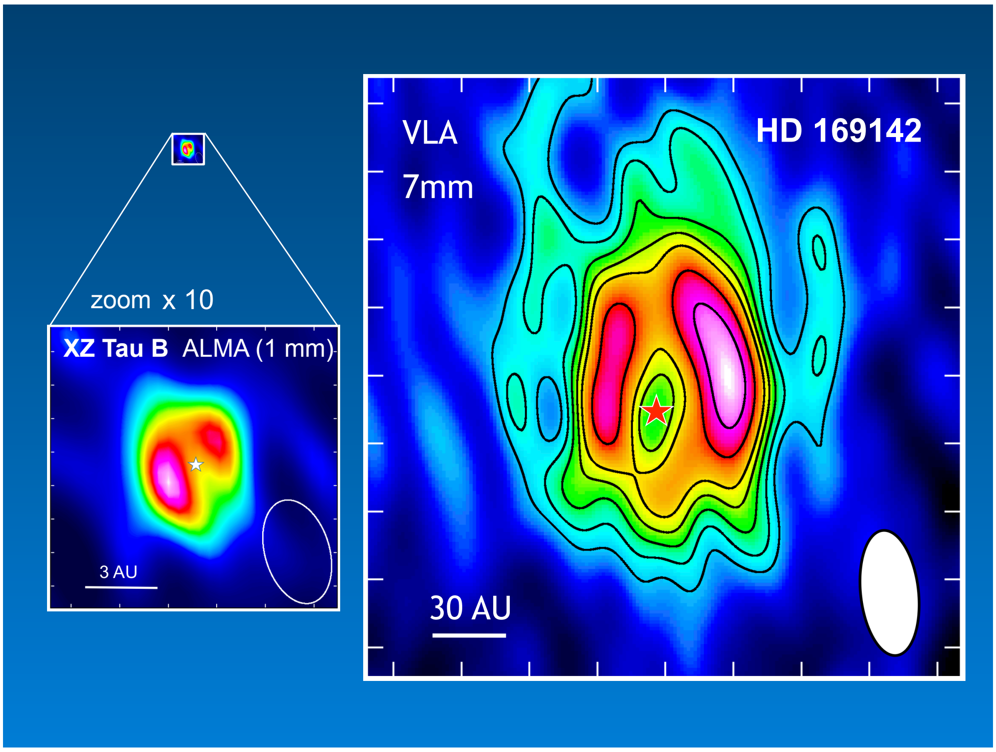

Figure 5: Comparison of the disks around the M2 star XZ Tau B and the Herbig Ae/Be star HD 169142. Beams are shown in the lower right corner. The decrease of emission toward the NE and SW edges is an observational effect partially produced by the elongation of the beam. Figure adapted from [11] and [12].

small circumstellar disk of dust with a central cavity similar to those observed in transitional disks, but on a much smaller scale.

To support our disk interpretation for XZ Tau B we carried out a detailed modeling and radiative transfer calculations to obtain the emerging emission in a similar way as we did for the HD 169142 disk (see Section 2). We used an updated version of the accretion disk models developed by [5]. We modeled the SED and the radial intensity profile of the ALMA image taking into account the contribution of the star, the disk and a possible ionized jet, although the contribution of this later component was found negligible. We ran a grid of models varying the mass accretion rate, the viscosity parameter (that is related with the disk turbulence), and the degree of settling (see [12]). Due to the scarcity of data, there were several possible solutions to explain the observed SED. Among these solutions, we selected the one with the minimum disk mass (10 M_{Jup}), and we found that even in this extreme case it would still have the capability to form planets. The shape of the intensity profile constrains the disk and cavity radii, providing a value of 3.4 au for the disk radius and a value of 1.3

au for the radius of the central cavity. Thus, we conclude that the modeling results are consistent with XZ Tau B being associated with a transitional disk. Typical transitional disks have radii of 50-100 au, with central cavities of 15-70 au in radii. The disk of XZ Tau B seems to be similar to those found in other young stars, but on a much smaller scale. This is the smallest disk ever imaged. Figure 5 shows a comparison of the XZ Tau B disk and the pre-transitional disk of HD 169142. The two disks show similar features, with signs of an azimuthal asymmetry suggesting the presence of a dust trap. Since the evolution of these features is determined by the orbital motions around the star, a tiny disk such as XZ Tau B is expected to evolve 50 to 500 times faster than its bigger counterparts. Therefore, small disks could reveal the complete planet formation process in short times scales.

The discovery of a dwarf disk in XZ Tau B suggests that protoplanetary disks could present a wide diversity of sizes, consistent with the diversity of sizes and architectures found in exoplanetary systems. Dwarf disks similar to that of XZ Tau B could be the precursors of low-mass compact multiple-planet systems such as those identified by the Kepler Mission ([9]) or the one recently found in the nearest star Proxima Centauri ([2].

5 The transitional protoplanetary disk around GM Auriga

GM Auriga is a star with 1.1 $M_\odot$ surrounded by a transitional disk with a cavity of radius $\sim$ 24 au ([6]). In the last years, optical and mid-IR forbidden line observations suggested that the GM Aur disk might be photoevaporating. Using the VLA we have recently imaged with high angular resolution and sensitivity the emission of GM Aur at cm wavelengths (see [10]). We have been able to separate in the images the contribution of the dust emission of the disk, the ionized jet perpendicular to it, and a possible photoevaporative wind from the disk. Figure 6 shows in color scale the dust emission of the disk at 7 mm, and in contours the ionized components at 3 cm (after subtraction of the dust contamination at this wavelength). As can be seen in the figure, one of the ionized components follows the same morphology of the disk, which has its major axis oriented in the NE-SW direction, and the other component traces a jet in a perpendicular direction. This is the first time that such a separation of the three components has been achieved, suggesting that a similar study could be undertaken in the future for a larger number of objects. This will allow us to better understand the role of these components in ending the accretion process, dispersing the gas in protoplanetary disks, and shaping the resulting planetary system.

6 Summary and conclusions

The four protoplanetary disks discussed in this paper illustrate how a combination of multiwavelength high angular-resolution observations and modeling of both the SED and the images offer a valuable opportunity to progress in the understanding of how planet-formation processes proceed.

Sources such as HL Tau reveal that disk fragmentation can start at a very early stage, likely forming the embryos of the first planets. The HD 169142 disk shows "signposts" of

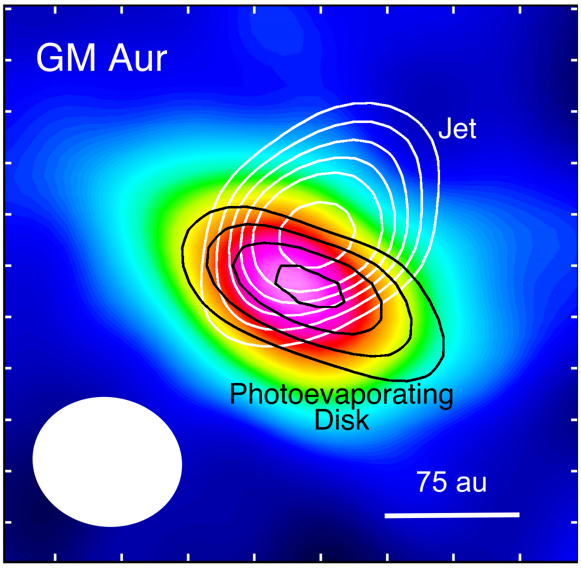

Figure 6: VLA imaging of GM Auriga. The color scale shows the dust emission of the disk at 7 mm. Contours show the ionized components of the emission at 3 cm: the radio jet is shown in white contours and the black contours trace the photoevaporative winds arising from the disk surface. The beam of the 3 cm observations is shown in the lower left corner. Figure adapted from [10].

ongoing planet formation, since it exhibits wide gaps and azimuthal asymmetries possibly tracing dust traps. Actually, this is one of the few disks where a compact infrared source within one of its gaps has been found, supporting the idea that protoplanets would have created such gaps. The GM Aur disk appears to be in a relatively advanced stage of evolution, showing both signs of planet formation and of photoevaporating material. A particularly remarkable case is the disk of XZ Tau B, which is much smaller than any protoplanetary disk ever detected. This is an important finding not only because it is small, illustrating that the diversity of architectures observed in exoplanetary systems can result from a similar diversity in their precursors, the protoplanetary disks, but also because its evolution would happen in very short timescales (months), that will allow us to know how the process occurs and shed light on the understanding of the evolution of this particular disk as well as its larger siblings.

Acknowledgments

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