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Planet formation in extreme conditions.

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Abstract

After the discovery of more than 5,000 exoplanets, one of the most striking aspects is the diversity of types found, as well as the diversity of architectures of exoplanetary systems. It is therefore reasonable to expect that a similar diversity should also be observed in their progenitors, the protoplanetary disks. I will focus on the observed diversity of protoplanetary disks, presenting some unique examples, taken from our recent research, that show planetary formation under extreme conditions. I will then present our work on dwarf protoplanetary disks around M-type dwarf stars, disks around very massive stars, and disks in multiple star systems, and discuss the implications for planetary formation.

1 Introduction

In the current paradigm ([20]), the stars are formed through the collapse of a fragment of a molecular cloud. At the very beginning of this process a central object is formed. This is the protostar. At the same time, because of the angular momentum conservation, a flattened structure is developed around the protostar, the accretion disk. In addition to accretion, a fraction of material is ejected in a direction perpendicular to disk. In this way, the excess of mass and angular momentum is removed. During the evolution of the process accretion and outflow coexist and are the hallmark of the current star formation paradigm. As time goes by, the envelope is being removed, accretion decreases and the star reaches its final mass. Also, the accretion disk becomes a planetary system. For this reason, these disks are called protoplanetary disks.

In the last 10 years, the focus of study of the earliest stages of star formation has shifted to the earliest stages of planet formation. This is because of the advent of the ultra-sensitive radio interferometers, such as the Atacama Large Millimeter/submillimeter Array (ALMA), the Very Large Array (VLA), and large infrared telescopes that have completely revolutionized the field. Thanks to these instruments, we have been able to detect several signatures of the onset of the planet formation process in many of these disks. Examples of these signatures are cavities, gaps, spirals, rings, walls, and azimuthal asymmetries. These signatures are attributed to the presence and perturbations produced by one or several planet embryos within the disk. A confirmation of this interpretation is the detection of infrared point sources within the cavities of some disks ([21], [11], [28]).

The most compelling case may be that of the PDS70 disk, where an infrared source at 20 au from the star is found inside the cavity. This has been interpreted as a protoplanet or substellar companion with an estimated mass of 10 Jupiter masses. The orbital period of this object is about 120 years. Another example is HD 169142, where a protoplanet candidate has been detected inside its cavity at similar distance and with a similar mass. These candidates can be confirmed if orbital proper motions are measured. Given the period of about 100 years, this can be done in the next few years.

The distinctive characteristic of the standard star formation paradigm is the presence of a disk-jet system. The presence of a disk makes the formation of a planetary system possible. However, the standard paradigm assumes isolated low-mass star formation. After the consolidation of this paradigm, it is worth asking whether it could also be extrapolated to other cases. Are disk-jet systems also present in other scenarios, for instance in multiple or even in high-mass star formation? Can planetary systems be formed in these scenarios? How are these planetary system expected to be?

Certainly, the study of these additional star/planet forming scenarios may provide the clues for a better understanding of the striking diversity of all the known exoplanetary systems that are being discovered. In this paper, I will present some striking results on protoplanetary disks associated with multiple or high-mass protostars, and discuss the possibility of planet formation under these extreme physical conditions.

2 Disks in binary or multiple systems

In the case of multiple star formation, the standard star formation scenario is not completely valid. Each protostar may develop its own disk and jet system, but the whole system is more complex. In a binary system, there might be up to three protoplanetary disks: two circumstellar disks (CS), and a circumbinary disk (CB) surrounding the two stars. In the case of a close binary, there may also be strong interaction between stars, even with matter exchange. The evolution of one star may affect the other one; actually, one of the protostars may be formed from the fragmentation of the disk of its companion. High angular resolution data ($< 1''$) are needed to disentangle the emission of each component, especially for those systems separated by less than 100 au. In summary, the standard paradigm of star formation may be used for the study of binary star formation, but it is more complex.

The development of different kinds of disks is confirmed by hydrodynamic simulations, demonstrating that the key parameter in disk formation is the specific angular momentum of the infalling gas [3]. This can be seen in Figure 1 which shows the distribution of material as a function of the specific angular momentum. According to these simulations, systems with low specific angular momentum, the material will only fall toward the primary (the more massive), forming a circumstellar disk. Systems with increasing specific angular momentum, part of material will also fall toward the secondary star, forming another circumstellar disk. If the specific angular momentum increased even more, circumbinary disk starts to appear,

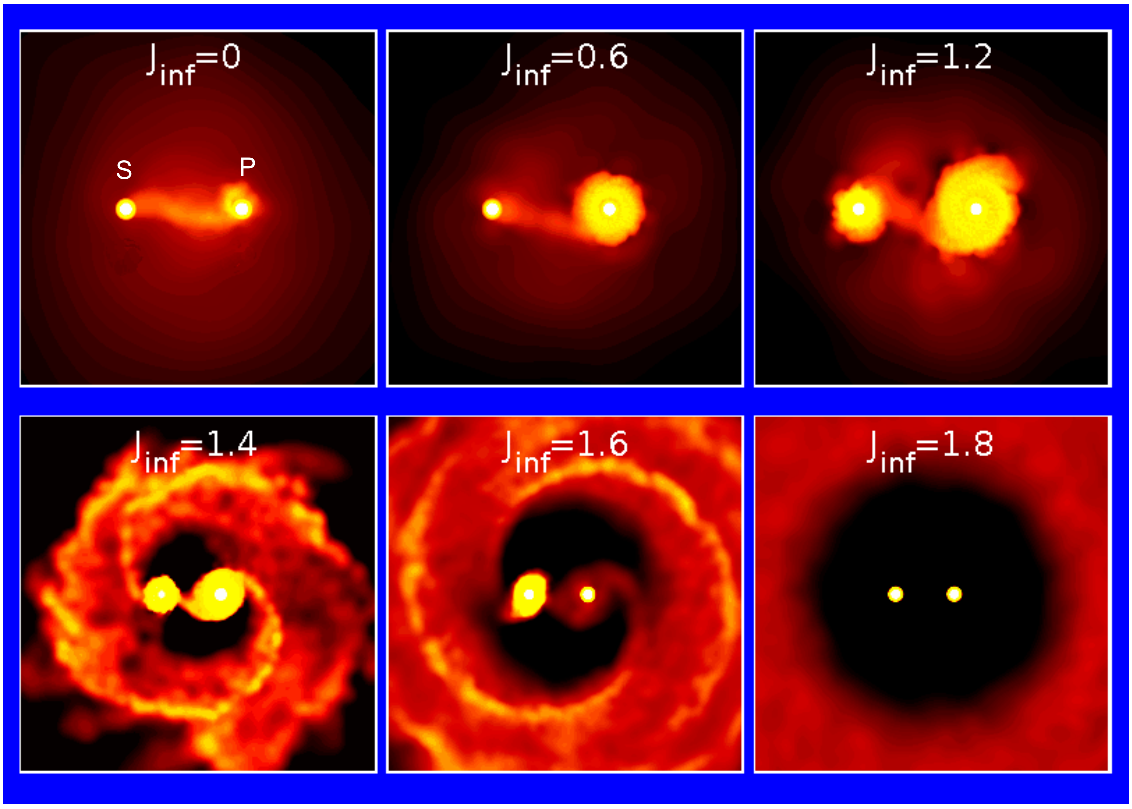

Figure 1: Hydrodynamic simulations of disk formation in a binary system as a function of angular momentum per unit mass, $J_{\rm inf}$. The more massive star is labeled as P (primary) and the less massive star is labeled as S (secondary). Credit:[3].

and if the specific angular momentum is very high all the material goes to the CB disk. In summary, a protobinary system might develop one, two or three protoplanetary disks.

The results of simulations are supported by ALMA observations as can be seen in Figure 2, which shows millimeter observations revealing a protobinary system where one circunstellar disk is brighter than the other, a system with two circumstellar disks of similar brightness and an example in which a circumbinary disk, in addition to the two CS disks is present. One of these cases is the L1551 IRS5 system, which is the first binary in which a clear disk/jet system associated with each star was discovered, suggesting that the formation of binary systems has shown similarities with the formation of isolated stars. VLA observations of L1551 IRS 5 show two disks ([22]), separated by 45 au, and two jets ([23]), so that each of two protostars is associated with a disk/jet system. The disks have a radius of only 10 au, which is one order of magnitude smaller than the typical radii of disks around single stars. The small radii of the disks can be explained as the result of tidal interactions between the stars. For this reason, the disks could be truncated at a size that is a fraction of the maximum

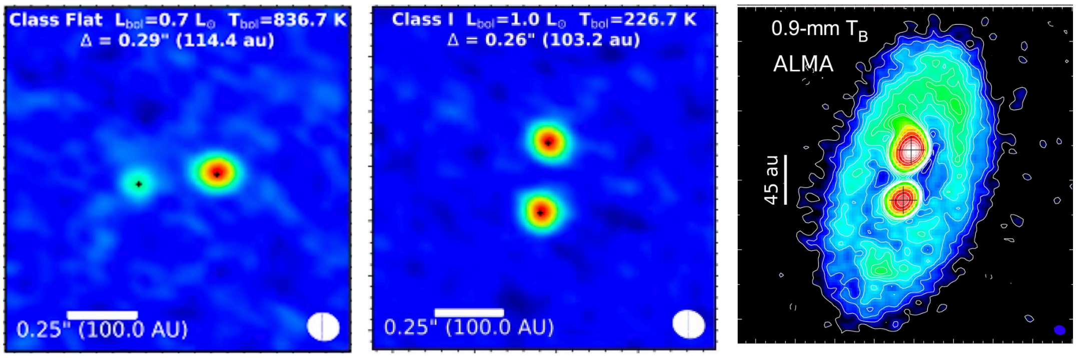

Figure 2: Dust emission of HOPS 242 (left) and HOPS 193 (center) circunstellar disks detected by ALMA at 870 μm in the Orion star forming region. Circunstellar and circumbinary dust disks of the L1551 IRS 5 protobinary system (right), in Taurus, detected by ALMA at 0.9 mm. Figures adapted from [26] and [24]. Other examples can be found on the website: *https://planetstarformation.iaa.es.*

separation between the stars. Twenty years ago, the system was modeled in great detail [18]. The model predicted that in addition to the CS disks a CB disk is required to explain the SED and mm images properly. Interestingly, ALMA has detected the circumbinary disk very recently ([24], [8]).

The SVS 13 proto-binary system is another case with a circumbinary disk. The CB disk shows prominent spiral arms extending up to $\sim$ 500 au (see left panel of Figure 3) that appear to converge mainly toward the position of the western source ([9]). Each source has a circumstellar disk with radius of $\sim$ 10 au. We have recently conducted a comprehensive observational study of this system to derive the physical and chemical properties of the disks as well as their kinematics ([9]). Compiling data from 30 years of observations, we have measured the orbital proper motions of the stars and found that they rotate counterclockwise. Combining the proper motions with the line of sight velocities, inferred from the molecular line observations, we obtained the 3D kinematics of the system.

Figure 3 (top-right panel) shows the mean velocity (in color scale) overlaid on the integrated intensity of the CS (J=7-6) rotational transition. The image clearly illustrates an east-west velocity gradient in the CB disk with a peculiar "yin-yang" shape. We interpreted this morphology as a combination of infall and rotation motions in this structure. Interestingly, there are a few Etylene Glycol transitions which are only detected in the western circumstellar disk (Figure 3, bottom-right panel), allowing the isolation of the western disk kinematics at scales of the order of 10 au, and to infer the stellar mass of this component ($0.3M_{\odot}$) by fitting a Keplerian rotating disk model to these transitions. We are currently working on radiative transfer models to further characterize the properties of the CS disks (see [16]) and on analyzing in detail the properties of the very high velocity outflow driven by this source ([6]).

The existence of planets around one of the stars or around each star of a binary, or even around the two stars, circumbinary planets, as predicted by the simulations and observations

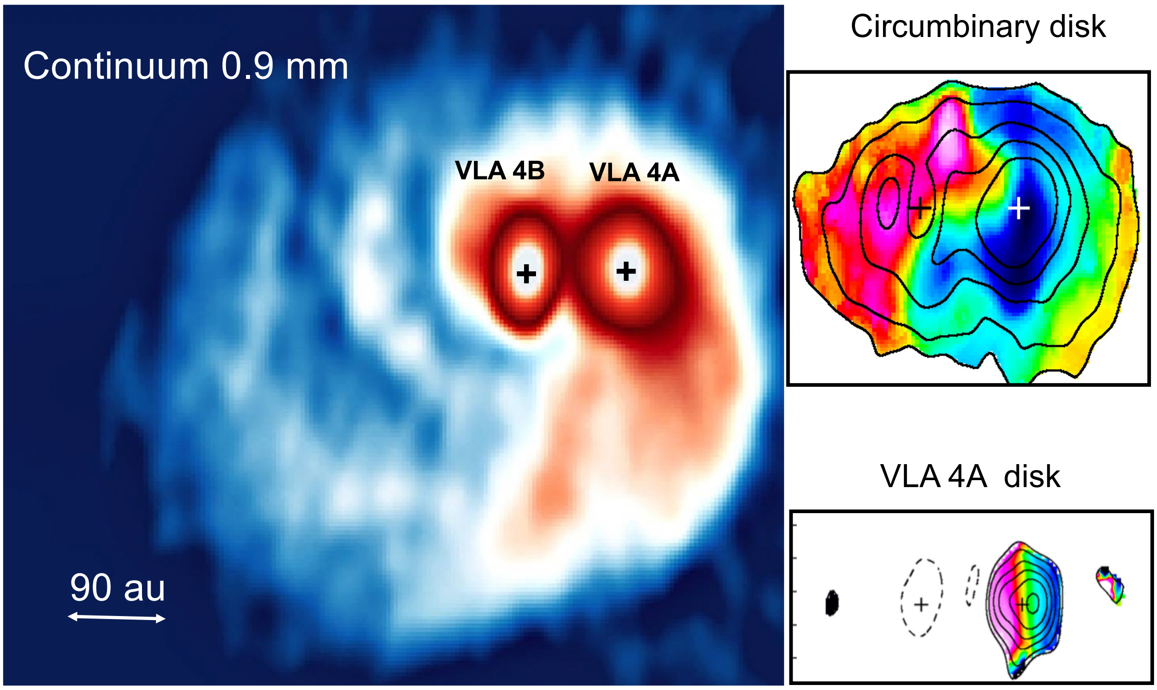

Figure 3: Dust emission of SVS 13 protobinary system in Perseus molecular cloud complex observed by ALMA at 9mm. Two circumstellar disks and a spiraling circumbinary disk are clearly detected in dust continuum emission (Left panel). Velocity-integrated emission (contours) overlaid on intensity-weighted mean velocity (color scale) of the CS (7–6) molecular lines observed with ALMA toward the circumbinary disk (Top-right panel). Velocity-integrated emission (contours) and intensity-weighted mean velocity (color scale) of the ethylene glycol lines associated with VLA 4A disk (Bottom-right panel). Figures adapted from [9].

of protobinaries has been confirmed by exoplanet observations. Recently, the TESS satellite has discovered a planet orbiting two stars in the system Kepler 34 ([12]).

In addition to the presence of several types of disks, another factor that increases the complexity of multiple star formation is the interaction between the stars. Recent simulations performed by ([4]), depicted in Figure 4, illustrate the matter exchange due to tidal interactions in the formation of multiple systems and also show spiral arms, fragmentation, merges, etc. These simulations take into account the formation of a cluster of about 100 stars. Each panel of Figure 4 is a close-ups of several groups of stars (white points), corresponding to a snapshot of the whole system at a given time.

In some cases there are two very close protostars and a third more separated one. Also there are tidal tails with a shape of spirals, produced by the interaction between components. The simulations also show four protostars, but they are grouped in close pairs, so that, at large scale appears as two stars. There is matter exchange between the protostars, and as the systems evolves, the relative masses of the disks and stars may change. Merging of two

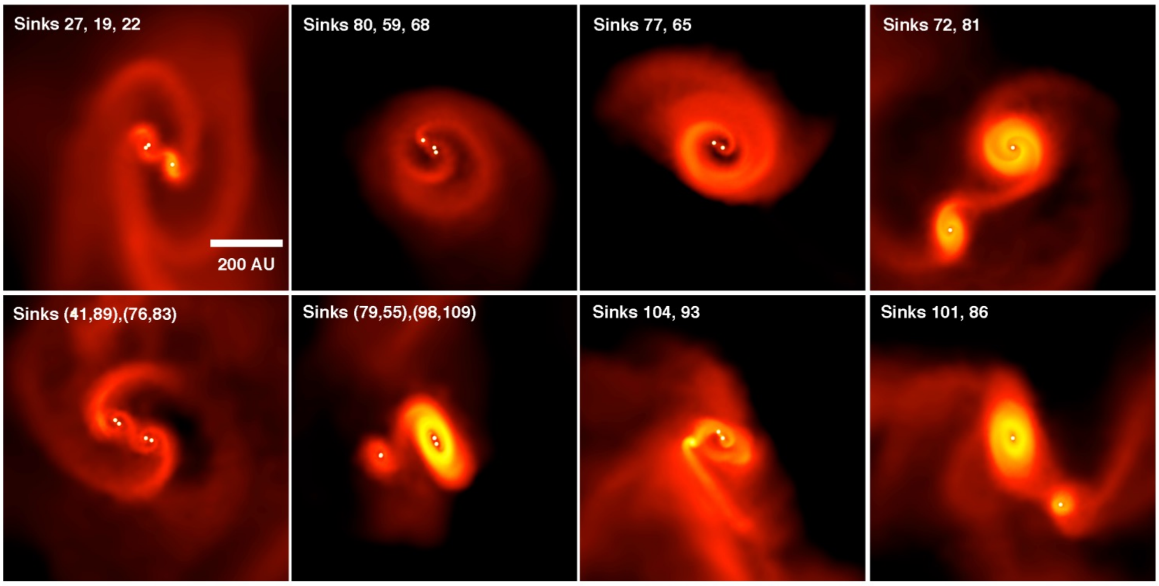

Figure 4: Hydrodynamic simulations of disk formation in binary systems and in multiple systems that take account matter exchange. Protostars or sink particles are plotted as white filled circles. Credit: ([4])

stars is also possible. Fragmentation of the disks also occurs, originating new stars. This is exactly what observations show, as can be seen in a gallery of disks observed with ALMA (Figure 5), where the formation of double, triple and high order stellar systems is revealed. In the protobinary system SVS 13 spiral arms can be observed ([9]), while in BHB 2007 system tidal tails ([1]) are observed. In fact, there is evidence of fragmentation, from which new stars are formed in L1448 system ([25]) and flybys in UX Tau A/C disk system ([27]). Even, in the most extreme cases, the interaction of a triple hierarchical system usually results in the ejection of the less massive star, while the other two stars remain gravitationally bound in a closer orbit. This may be the case o of our nearest neighbor Alpha Centauri, where the less massive component, Proxima, is located at a much larger distance ($\sim$ 10000 au) from the other two components. These interactions will be reflected in the final result: the exoplanetary systems.

3 Dwarf disks

One of the most striking results of the study of exoplanets is the diversity of planets from super-Earth to mini-neptunes and their configurations. It is particularly noteworthy, the small exoplanetary systems discovered by Kepler mission. Although there may be strong observational biases, Kepler has found planetary systems really small planetary systems, with many planets orbiting within a radius smaller than 1 au. Kepler 11 ([15]) is a prototypical example of the so-called closely packed exoplanetary system, in which a large number of

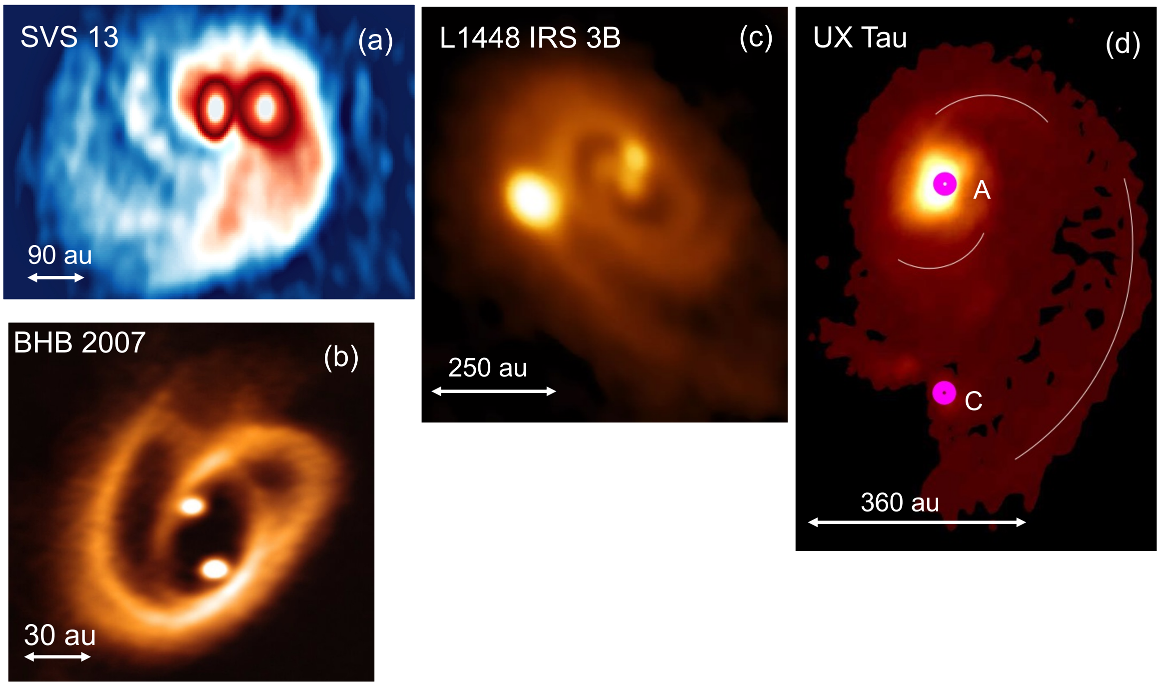

Figure 5: Gallery of disks in multiple young stellar systems observed by ALMA in the submillimeter regime. Panel a) protobinary system SVS 13 ([9]), Panel b) protobinary system BHB 2007 ([1]), Panel c) triple system L1448 IRS 3B ([25]), and Panel d) multiple system UX Tau ([27])

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planets are found within a small radius. In fact, in these systems all the stable orbits are occupied by a planet. Within the orbit of Venus our Solar system has only Mercury, while Kepler 11 has 6 planets. Trappits 1 also fall into this category. Which is the origin of these compact exoplanetary systems? Do compact exoplanetary systems originate from dwarf protoplanetary disks? There is evidence of an extremely small disk from which the compact exoplanetary systems may originate.

A few years ago we reported the detection of a circumstellar disk of only 3 au radius ([19]). This disk belongs to the protobinary system XZ Tau (located at 4200 au from the well-known HL Tau disk), whose components are separated by 40 au. The large improvement in the angular resolution of ALMA allow us to probe scales of only 2 au. Figure 6 shows HL Tau and XZ Tau B disks at the same scale in order to see how small XZ Tau B is. Interestingly in this small disk signs of the onset of planet formation can be seen, e.g., the decrease in the emission towards the center may be indicating a small cavity and the slight azimuthal asymmetry, with the SW side brighter than the NW side, could be a dust trap. To test the disk interpretation, we modeled ([19]) the compact dust emission to reproduced the SED and the 1.3mm spatial profile obtained by ALMA. Despite the scarcity of data, for which many solutions are posible, we see the model predicts a disk with enough mass to form

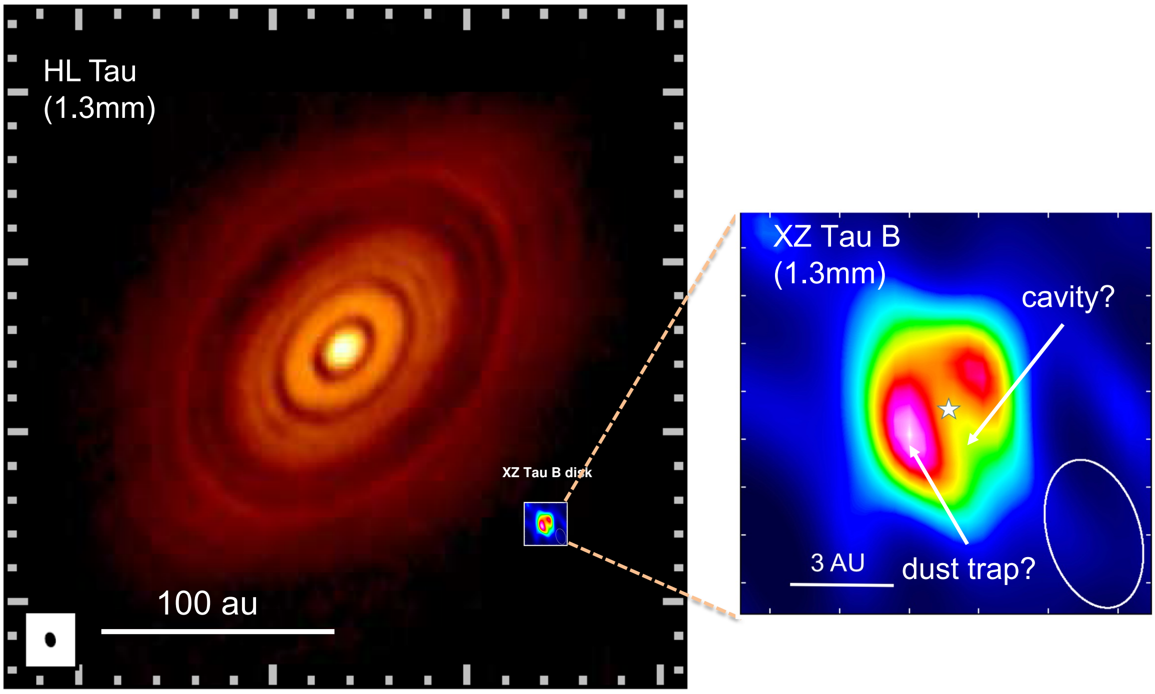

Figure 6: Left: Comparison of the HL Tau and XZ Tau B disks at the same scale. Right: Close-up of XZ Tau disk showing some possible features of planet formation.

planets (Mass >9 M_{Jup}) even though it is very small.

If planet formation is feasible in XZ Tau B, such disks could be the precursors of compact exoplanetary systems. A large population of these very small disks could exist, but has remained hidden because only a few extremely high angular resolution observations have been made so far.

4 Disks around high-mass protostars

Finally, the case of high-mass star formation and the possibility of planet formation in these stars is discussed. If massive stars could be formed by accretion, with a disk/jet system, then, in principle, a planetary system could be formed from the circumstellar disk. However, there are some important differences between low-mass star and high-mass star formation, for example, the evolution of massive stars is faster than that of low-mass stars, massive stars reach the main sequence when they are still accreting material from their maternal cloud, and in addition they are born in crowded regions, which makes the process more complex. Massive stars develop HII regions with a high UV photon rate. Radiation pressure and intense stellar winds of these stars may halt the collapse, so that the star cannot continue growing and reach a high mass. Therefore, it has been debated in recent years whether it is possible to form high-mass stars by accretion.

Two main mechanisms have been proposed to form high-mass stars: the coalescence scenario in which a massive star is formed by collisions of low-mass stars. The other scenario is the monolithic accretion, which is a scaled version of the standard scenario for low-mass stars formation. The coalescence scenario has the problem that the time between collisions is much longer than age of the cluster where the massive star is born, however, it may be the only way to form extremely massive stars (~ 100 $M_\odot$).

As mentioned before, the accretion scenario may have a problem with the radiation pressure, however, detailed radiative transfer calculations ([17]) show that it is possible to form stars up to 30 $M_\odot$. Moreover, the observations show that massive stars are associated with disk/jet systems ([5]) similar to those found in low-mass stars. Since disks and jets are not expected to survive after the collisions, their detection is taken as a strong argument in favor of the accretion scenario.

One of the most remarkable cases is that of the high-mass protostar HH80, where a clear disk/jet system is associated with a star of 20$M_\odot$. Figure 7 shows this spectacular system, consisting of a disk (observed by ALMA at 1.14mm, [13]) with a radius of 200 au and a radio-jet clearly perpendicular to the disk (observed by the VLA at 3.6 cm, [7]). We believe this is a genuine accretion disk around a 20 $M_\odot$ protostar. We have also carried out polarization observations ([13]) from which dust properties can be inferred using the polarization pattern and assuming that scattering is the dominant mechanism. This is important to model the disk. We have performed radiative transfer models to reproduce the image at 1.14mm obtained by ALMA ([2]). The model takes into account stellar irradiation, viscosity dissipation and the accretion shock which is a relevant source of heating due to the high-mass accretion rates of high-mass stars ([17], [10]).

From the modelling, several disk parameters can be inferred, for instance, the disk mass (5 $M_\odot$), its stability, the ratio between mass accretion rate and viscosity and also its physical structure (see [2]). We found that this disk is very hot, with temperatures above 100K everywhere. As a consequence of the high temperature of the disk, no solid-phase molecules, such as water or CO, are expected to survive. Condensation fronts, also called snow lines, must be near the edge of the disk, in the envelope surrounding it. Therefore, the formation of giant gas planets, such as Jupiter, within the disk is not expected unless they form at great distances from the star. This is consistent with the recent finding of an exoplanet at a distance of 500 au from the massive b Centauri star ([14]), that has been detected by direct imaging.

5 Summary of the results:

The diversity observed in exoplanetary systems can reflect the diversity of scenarios in the formation of protoplanetary disks.

We find that disks in binary protostars are in agreement with exoplanet observations, since exoplanets have been discovered around already formed binary stars.

We propose that dwarf disks are possible precursors of closely packet compact exoplanetary systems discovered by Kepler mission.

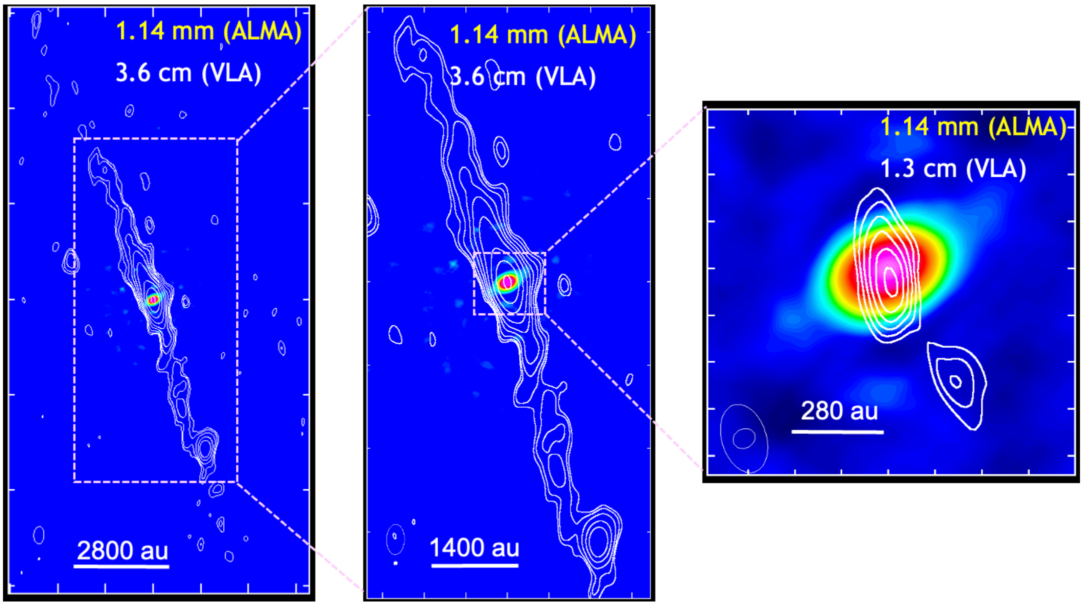

Figure 7: Sequence of amplifications of the disk/jet system associated with the high-mass protostar HH80. The dust continuum emission from the disk (ALMA at 1.14 mm, color scale) has a radius of $\sim$ 200 au. The free-free emission (contours) associated with the radio-jet, traced by the VLA at 3.6 cm (left and center panels) and 1.3 cm (right panel), is seen clearly perpendicular to the disk. The ALMA and VLA beams are shown in the lower left corner of each panel. Figures adapted from [13], [7], [2].

Finally, we find that disks in massive protostars can form Jupiter planets only at large distances from the star, which is supported by the recent finding of an exoplanet candidate, orbiting a 6 $M_\odot$ star, at a large distance of 500 au.

Acknowledgments

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References

[1] Alves, F. O., Caselli, P., Girart, J. M. et al. 2019, Science, 366, 90

[2] Áñez-López, N., Osorio, M., Busquet, G. et al. 2020, ApJ, 888, 452

[3] Bate, M., Bonnell, I.A. 1997, MNRAS, 285, 33

[4] Bate, M. 2018, MNRAS, 475, 561

[5] Beltran, M. T., de Wit, W. J. 2016, A&ARv, 24, 6

[6] Blázquez-Calero et al. 2023, in "Highlights of Spanish Astrophysics XI, Proceedings of the XV Scientific Meeting of the Spanish Astronomical Society (La Laguna, Spain 2022), M. Manteiga, L. Bellot, P. Benavidez, A. de Lorenzo-Cáceres, M. A. Fuente, M. J. Martínez, M. Vázquez- Acosta, C. Dafonte (eds.), 2023

[7] Carrasco-González, C., Galván-Madrid, R., Anglada, G. et al. 2012, ApJL, 752, L29

[8] Cruz-Sáenz de Miera, F., Kóspál, Á., Ábrahám, P., Liu, H. B., Takami, M. 2019, ApJL, 882, L4

[9] Diaz-Rodriguez, A. K., Anglada, G., Blázquez-Calero, G., et al. 2023, ApJ, 930, 91

[10] De Buizer, J.M., Osorio, M., Calvet, N. et al. 2005, ApJ, 635, 452

[11] Keppler, M., Benisty, M., Müller, A. et al. 2018, A&A, 617, 44

[12] Kostov, V. B., Powell, B. P., Orosz, J. A. et al. 2021, AJ, 162, 234

[13] Girart, J. M., Fernández-López, M., Li, Z. -Y., et al. 2018, ApJL, 586, L27

[14] Janson, M., Gratton, R., Rodet, L. et al. 2021, Nature, 600, 231

[15] Lissauer, J. J., Fabrycky, D. C., Ford, E. B. et al. Nature, 470, 53

[16] Navarro, R., Osorio, M., Blázquez-Calero, G. et al. 2013, poster number: DOI 10.5281/zenodo.7050035 in "Highlights of Spanish Astrophysics XI, Proceedings of the XV Scientific Meeting of the Spanish Astronomical Society (La Laguna, Spain 2022), M. Manteiga, L. Bellot, P. Benavidez, A. de Lorenzo-Cáceres, M. A. Fuente, M. J. Martínez, M. Vázquez- Acosta, C. Dafonte (eds.), 2023

[17] Osorio, M., Lizano, S., D'Alessio, P. 1999, ApJ, 525, 808

[18] Osorio, M., D'Alessio, P. Muzerolle, J., Calvet, N., Hartmann, L., 2003, ApJ, 586, 1148

[19] Osorio, M., Macías, E., Anglada, G. et al. 2016, ApJ, 825, 10

[20] Shu, F. H., Adams, F. C., Lizano, S. 1987, ARA&A, 25, 23

[21] Reggiani, M., Quanz, S. P., Meyer, M. R., et al. 2014, ApJL, 792, L23

[22] Rodríguez, L. F., D'Alessio, P., Wilner, D. J., et al. 1998, Nature, 395, 355

[23] Rodríguez, L. F., Porras, A., Claussen, M. J., et al. 2003, ApJL, 586, L13

[24] Takakuwa, S., Saigo, K., Matsumoto, T. et al. 2020, ApJ, 898, 10

[25] Tobin, J. J., Kratter, K. M., Persson, M. V. 2016, Nature, 538, 483

[26] Tobin, J. J., Sheehan, P. D., Megeath, S. T. et al. 2020, ApJ, 890, 130

[27] Zapata, L. A.; Rodríguez, L. F.; Fernández-López, M. et al. 2020, ApJ, 896,132

[28] Zhou, Y., Sanghi, A., Bowler, B. P. et al. 2022, ApJ, 934, 13