*Highlights on Spanish Astrophysics IX, Proceedings of the XII Scientific Meeting of the Spanish Astronomical Society held on July 18 – 22, 2016, in Bilbao, Spain. S. Arribas, A. Alonso-Herrero, F. Figueras, C. Hernández-Monteagudo, A. Sánchez-Lavega, S. Pérez-Hoyos (eds.)*

# Circumstellar disks and planetary formation

**Nuria Huélamo**[1]

[1] Centro de Astrobiología (INTA-CSIC)
ESAC, Camino bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain
nhuelamo@cab.inta-csic.es

## Abstract

Circumstellar disks are very common around young intermediate-, low-mass stars, and brown dwarfs. They are the cradle of planetary systems, although the mechanism to form planets is still unknown. In this text I review some advances in the field of circumstellar disks and planetary formation coming from observations.

## 1 Introduction

Circumstellar disks (CDs) are common around intermediate-, low-mass stars, and substellar objects. They are the cradle of planetary systems, although the planet formation mechanism is still unknown.

CDs were first inferred by the infrared excesses detected in the spectral energy distributions (SEDs) of young stars (see Fig. 3). With the advent of more sensitive diffraction-limited observations, it has been possible to spatially resolve these disks and derive important properties, like sizes, composition, masses, etc.

In the next sections I will summarize some of their properties and describe different studies focused on the disk-planet connection.

## 2 Main properties of circumstellar disks

As stated above, one important property of CDs is that they are common around young objects with different stellar masses, from intermediate–mass stars to brown dwarfs. Since they are the cradle of extrasolar planets, a big effort has been made to derive their main properties and to relate them with the process of planetary formation.

The sizes of CDs have been studied using different observational techniques, and show a wide range of values. For example, [48] analyzed $HST$ observations of a sample of proplyds

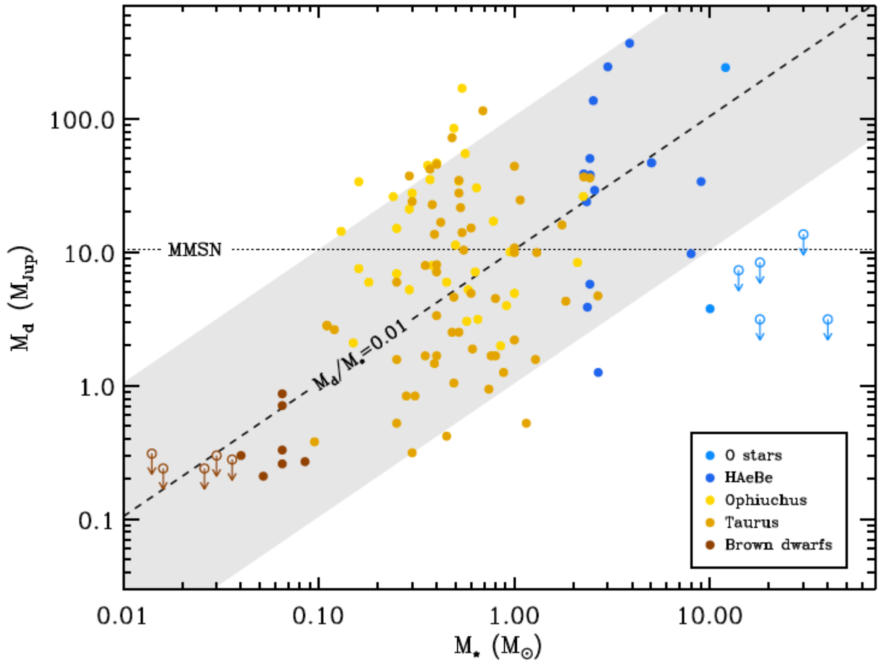


Figure 1: The disk mass as a function of the stellar mass (adopted from [51])

and silhouette disks (i.e. disks observed in absorption over the very bright nebular emission) aroung G and M-type stars in Orion. They reported that 40% to 45% of the Trapezium cluster disks have radius larger than 50 AU, with a median radius of 75 AU. They did not report any correlation between the stellar mass and the disk diameter. On the other hand, sub(mm) interferometric observations of disks are sensitive to the bulk of the dust emission. [13] analyzed resolved observations of eight late-type stars stars in Taurus, and derived outer radii equal or larger than 150 AU, with most of the emission concentrated within a radius of 300 AU. It is important to note that very high angular resolution observations of disks have revealed different sizes for the gaseous and dust disk, being the former normally larger than the latter(see e.g. [33, 23, 14, 21]). A collection of spatially resolved disks, including the observational technique used, can be found in *http : //www.circumstellardisks.org*.

In the case of brown dwarfs (BDs), it has been difficult to spatially resolve their disks. [28] presented HST observations of a BD disk that was marginally resolved and derived a radius between 20-40 AU. It was not until 2013 that [42] presented the first spatially resolved thermal emission from a disk around a BD, reporting a disk radius between 15-30 AU. One year later, [43] spatially resolved three more BD disks with ALMA, reporting sizes larger than 70 AU in radius. Interestingly, the inferred disk radii, the radial profiles of the dust surface density, and the disk to central object mass ratios lie within the ranges found for disks around more massive young stars.

The mass of CDs is also an important property, since it can be compared with the minimum-mass solar nebulae. (Sub)millimetre observations are the best ones to derive disk

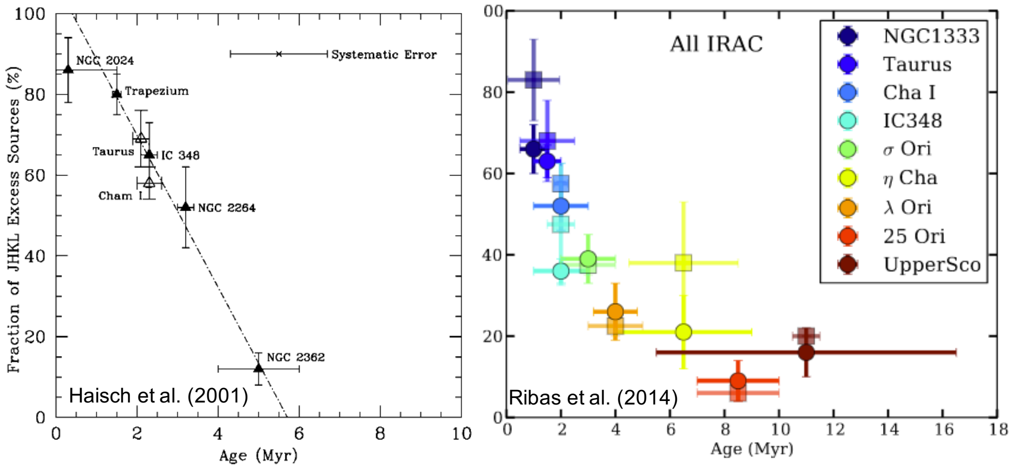


Figure 2: Disk lifetimes estimated from near-IR excesses [17] (left panel), and mid-IR data [39] (right panel). The right panel includes the comparison of the disk fractions obtained in [39] (circles) with those from [18, 19] (squares).

masses since the emission is optically thin (except in the innermost regions). As a result of sub-mm surveys, it has been estimated an average mass of 5 $M_{Jup}$ around late-type stars. Interestingly, it seems to be a correlation between the stellar and disk mass from B-type stars to BDs. The median ratio of the disk mass to the stellar mass is of 1%, but with a very high dispersion (see Figure 1, and the review by [51]). In any case, we should note that the mass estimations are affected by large uncertainties in the dust opacity, the gas to dust mass ratio, and also by the grain growth within the disk, since it is difficult to estimate how much mass is hidden in very large grains.

One necessary ingredient for planet formation is the growth of dust grains from sub-micron to mm sizes, which is also related with the dust settling in the disk midplane. Grain growth has been extensively studied in CDs mainly through the analysis of the silicate feature at 9.7$\mu$m, which is sensitive to micron-sized dust grains. *Spitzer* and its mid-IR spectrometer IRS has contributed significantly to this field by observing hundreds of young stars within a wide mass range (see e.g. [4, 32, 31]). These studies showed that dust processing and grain growth are common in stellar (both in Herbig AB and low-mass stars) and susbtellar objects, and that can be observed at very early stages of disk evolution [15]. The presence of large grains can also be studied through the modelling of the SED in the (sub)mm regime. If grain growth is present, the slope at sub(mm) wavelengths is expected to be shallower than in the ISM, with typical values of $\alpha_{mm}$ ∼2-3. Indeed, the presence of mm-sized dust grains have been inferred in a large number of protoplanetary disks (e.g. [41, 46, 34]). Observations at *cm* wavelengths are also be very useful to detect even larger dust grains [52, 53], but are more difficult because the thermal emission decreases at longer wavelengths while the contribution from free-free emission coming from jets and/or photoevaporated disks can be significant (see e.g. [29]). One of the major challenges of current planet formation theories is to explain the growth of these dust grains to kilometre size bodies, the so-called "radial drift barrier" e.g.

(see [45]).

One of the most studied properties of CDs is their survival time, since it is directly related with the timescale to form planetary systems. In 2001, [17] presented a study of disk lifetimes based on $JHKL$ data of different star forming regions and conclude that the overall disk lifetime was ∼6 Myr (see Figure 2). Near-IR data is sensitive to the hot dust close to the star, so it is tracing the inner parts of the disk. Later-on, several studies focused on mid-IR wavelengths (sensitive to colder dust) conclude that primordial disks disappear between 10-20 Myr (see e.g. [19, 20, 39]).

Several works have suggested that disk evolution is related with the mass of the central objects, with disks around intermediate-type stars being dissipated faster than those around late-type stars and BDs (see e.g. [9, 11, 40]). Taking into account the *Spitzer* observations of young clusters, it seems that disk lifetimes around intermediate-mass stars are ∼2 times shorter than in late-type stars. One suggested explanation is the strong radiation from the central object that can photoevaporate the disk very efficiently.

All the works mentioned above are related with the dust survival within the disks. Regarding the gas lifetime, the *Herschel* observatory observed a large sample of young stars and study their gas content through the analysis of the [OI] line at 63.2 $\mu$m (see GAPS survey, [12]). As a result, they show that for the whole sample of observed T Tauri stars, the fraction with gas-rich disks is ∼18% at ages of 0.3–4 Myr, and 1–7% at 5–10 Myr. None are detected beyond 10 Myr.

# 3 Transitional disks and planetary formation

Some circumstellar disks showed SEDs with a deficit of mid-IR emission at wavelengths between ∼8-20 $\mu$m. This deficit was explained by a lack of dust at a given separation of the star, and later confirmed by high-resolution sub-mm observations that spatially resolved dust holes and gaps within the disks (see Figure 3) [8, 7, 2]. These disks have been called transitional disks. Some of these objects still display stellar accretion, suggesting the presence of an inner disk. In this case, they are known as pre-transitional disks.

Several mechanisms have been proposed to explain the origin of dust gaps in transitional disks (e.g. photoevaporation, grain growth), being the most exciting one the dynamical clearing by a young planet. If indeed the planets are the clearing agent, different theories claim that a companion body smaller than a certain threshold mass will allow some gas and small dust grains to accrete through its orbit feeding the inner disk (e.g. [27, 24]). The threshold mass depends on many parameters but reported values are between 1 and 10 $M_{\rm Jup}$ [27]. This implies that the dust gaps are not expected to be completely empty but filled with some gas and dust.

Thanks to powerful instruments, it has been possible to study the content of the gaps in the transitional disks. For example, [35] performed spectro-astrometry in the near-IR with CRIRES at the VLT, and detected gas within the gaps of three transitional disks. More recently, [47] have presented high-resolution and high sensitivity ALMA observations of four disks. They spatially resolve the dust and gas gaps, deriving their sizes and their content:

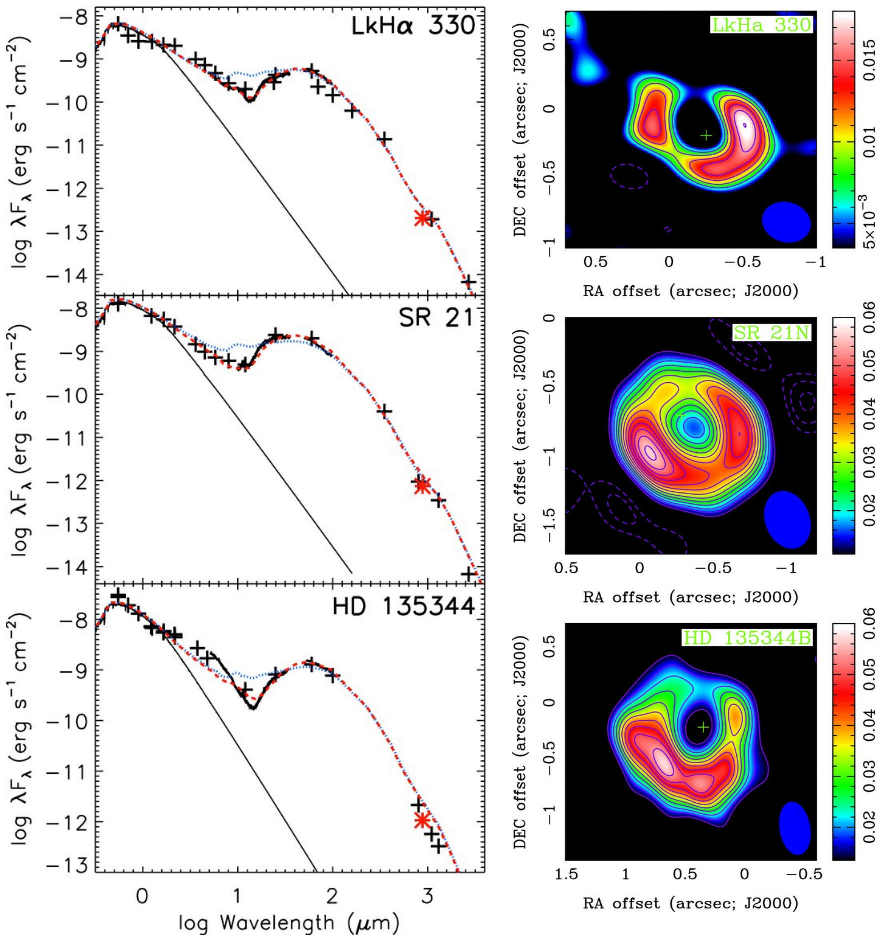


Figure 3: Left: Spectral Energy distributions (SEDs) of three transitional disks. The red (dashed) and blue (dotted) lines represent disk models with and without including a dust hole, respectively. The solid line represents the photospheric emission. Right: sub-mm observations of the three disks, displaying a clear dust hole in the central regions (adopted from [7]).

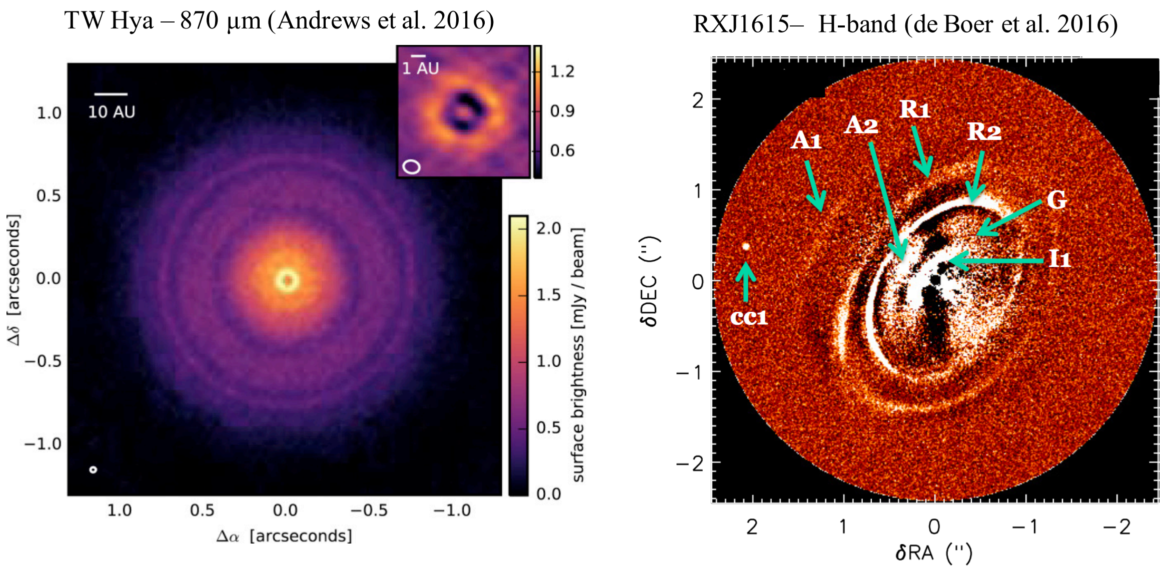


Figure 4: Left: ALMA sub-mm observation of the disk around TW Hya (adopted from [3]). Right: Near-IR image of the disk around RXJ1615 obtained with SPHERE/IRDIS at the VLT (from [6]). The images show several gaps and bright rings within the disks of the two objects. In the case of RXJ1615, the authors have reported the presence of two rings (R1 and R2), two arcs (A1 and A2), the inner disk (I1) and a companion candidate (cc1).

they show that the gas gaps are up to three times smaller than the dust ones in the four disks, and they are not completely empty.

Very high angular resolution observations have revealed the presence of not one but several gaps and bright rings within some transitional disks. This is the case of TW Hya, imaged by ALMA in the sub-mm and with VLT/SPHERE in the optical and near-IR range [3, 5], or the transitional object RXJ 1615, imaged in the near-IR with VLT/SPHERE [6] (see Figure 4). In fact, these multiple gaps and rings have been also detected in very young objects, like the Class I star HL Tau [1].

The dust rings and gaps can be explained in the context of the disk-planet interaction, but another explanation could be the presence of snow-lines of different volatiles at given separations from the star. A snow-line is a region of a protoplanetary disk at which a major volatile reaches its condensation temperature. Therefore, each ring within the disk may correspond to the condensation front of a different molecule (like e.g. water, CO, $CO_2$). In fact, the snow-line of the CO has been imaged in the disks of TW Hya and HD163296 [36, 37, 16]. In the case the water snow-line, it is expected to be placed very close to the star, at separations smaller than 10 AU, so it is more difficult to detect. One exception is the case of V883 Ori, a very young object with eruptive episodes. The target was observed by ALMA, and the authors reported the detection of the water snow-line at a radius of ~40 AU from the star. This displacement can be explained due to the increase of the disk temperature during a protostellar outburst [10]. Since accretion is very common in young stellar objects, the authors

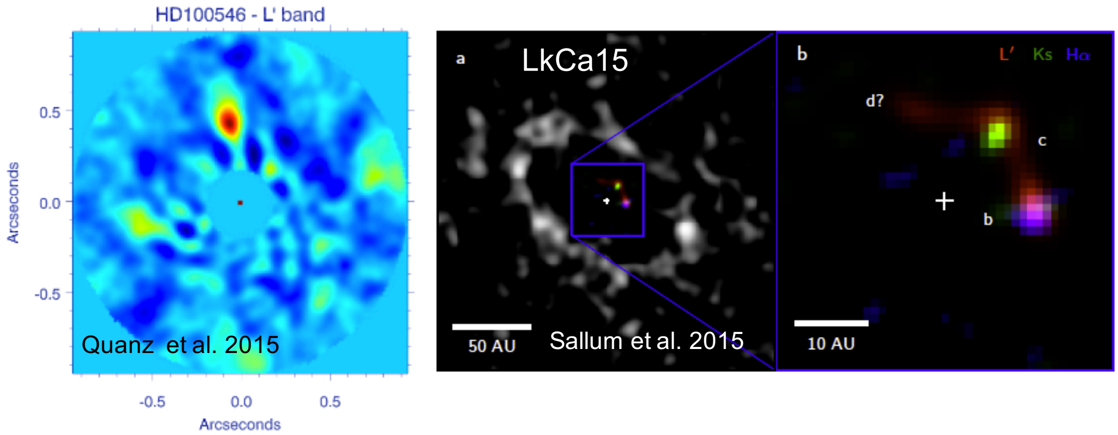


Figure 5: Detection of protoplanets within the gaps of transitional disks. Left: NACO/VLT L' image of the companion to HD100546 obtained through differential imaging observations (adopted from [38]). Middle and right panels: the protoplanet LkCa15b as detected with SAM in the near-IR and with direct imaging in the $H_\alpha$ filter (adopted from [44]).

conclude that highly dynamical water snow-lines must be considered when developing models of disk evolution and planet formation.

## 3.1 Protoplanets in transitional disks

Since transitional disks show signatures of planet formation, is it possible to detect faint protoplanets within their gaps? According to evolutionary models, young planets are expected to emit most of their light in the infrared regime, so high angular resolution and sensitive observations are needed at these particular wavelengths. High contrast images of transitional disks have been obtained with different techniques resulting in the detection of several protoplanets: for example, [38] confirmed a protoplanet embedded in the disk of the Herbig Ae/Be star HD 100546 using angular differential imaging with NAOS-CONICA (NACO) at the VLT. Another protoplanet, LkCa15 b, was detected in the near-IR through AO sparse aperture masking (SAM) techniques [25, 44]. Interestingly, the near-IR colors of these two protoplanets are extremely red, suggesting the presence of circumplanetary material. In a near future, we will probably witness the first detection of a circumplanetary disk with ALMA.

[26] have explained that planets might also accrete material from their circumplanetary disks. Recent studies have focused on studying early protoplanetary accretion using the same indicators as in T Tauri stars and BDs, e.g. the $H_\alpha$ line. [50] tried to detect accretion onto the planet LkCa15b through spectro-astrometry observations performed with XSHOOTER at the VLT. Since this instrument provides simultaneous spectra in the optical and near-IR range, they used different accretion tracers to detect LkCa15b, e.g. the $H_\alpha$, $Pa_\gamma$, and $Pa_\beta$ lines. They did not detect the protoplanet but could provide an upper limit to its accretion rate. Later in 2015, [44] presented the first $H_\alpha$ image of a protoplanet using the Magellan

Adaptive Optics (MagAO) system. Thanks to these observations, they derived the presence of very hot gas (∼10, 000 K) falling into the accreting protoplanet.

### 3.2 Complex Organic Chemistry and the origin of life

ALMA has already provided impressive images of protoplanetary disks. However, it has also opened a window to study complex organic chemistry during the formation of planetary systems. As an example, [30] have presented the first detection of a complex molecule (methyl cyanide) in the disk of the young star MWC480. Their overall results suggest that the rich organic chemistry of our solar nebula was not unique. ALMA has also provided the first detection of gas-phase methyl alcohol, methanol, in a planet-forming disk (TW Hya, [49]). Methanol, a derivative of methane, is one of the largest complex organic molecules detected in disks to date. The importance of this detection is that methanol is a building block for life, so it opens a window to understand our own solar system. In the next years, ALMA will probably provide outstanding results in this research field.

## 4 Future prospects

In the near future, the James Webb Space Telescope (JWST) will significantly improve our knowledge of circumstellar disks and planetary systems. In particular, observations with its near- and mid-IR spectrographs will shed light on the properties of warm dust within the disks, and the chemical composition of the protoplanet atmospheres. In the far future, projects like the TMT or the E-ELT, equipped with near- and mid-infrared imagers and spectrographs, will provide unprecedented angular resolution and sensitive observations from the ground.

## Acknowledgments

I am indebted to the SOC for inviting me to give this presentation.

## References

[1] ALMA partnership, Brogan, C.L., Pérez, L. et al, 2015, ApJ 808, L3

[2] Andrews, S.M., Wilner, D.J.; Espaillat, C. et al., 2011, ApJ 732, 42

[3] Andrews, S., Wilner, D.J., Zhu, Z., et al., 2016, ApJ 820, 40

[4] Apai, D., Pascucci, I., Bouwman, J. et al., 2005, Science 310, 834

[5] van Boekel, R., Henning, T., Menu, J., et al., 2016, ApJ, in press,

[6] de Boer, J., Salter, G., Benisty, M., et al., 2016, A&A in press

[7] Brown, J. M., Blake, G. A., Qi, C., Dullemond, C. P. et al., 2009, ApJ 704, 496

[8] Calvet, N., D'Alessio, P., Hartmann, L., et al., 2002, ApJ 568, 1008

[9] Carpenter, J.M., Mamajek, E.E., Hillenbrand, L.A. et al., 2006, ApJL 651, 49

[10] Cieza, L., Cassasus, S., Tobin, J. et al., 2016, Nature 535, 258

[11] Currie, T, Lada, C.J., Plavchan, P. et al., 2009, ApJ 698, 1

[12] Dent, W., Thi, W.F., Kamp, I. et al., 2013, PASP 127, 477

[13] Dutrey, A., Guilloteau, S., Duvert,G., et al., 1996, A&A 309, 493

[14] de Gregorio-Monsalvo, I., Menard, F., Dent, W., et al., 2013, A&A 557, 133

[15] Furlan, E. Watson, D.M., McClure, M.K. et al., 2009, ApJ 703, 1964

[16] Guidi, G., Tazzari, M., Testi, L., et al., 2016, A&A 588, 112

[17] Haisch, K., Lada, E.A., and Lada, C.J., 2001, ApJ 553, 153

[18] Hernández, J., Hartmann, L., Megeath, T., et al. 2007b, ApJ, 662, 1067

[19] Hernández, J., Hartmann, L., Calvet, N., et al. 2008, ApJ, 686, 1195

[20] Hillenbrand, L., 2008, Physica Scripta 130, 4024

[21] Huélamo, N., de Gregorio-Monsalvo, I., Macias, E., et al., 2015, A&A 575, L5

[22] Hughes, A.M., Wilner, D.G, Qi, C., et al., 2008, ApJ 678, 1119

[23] Isella, A., Testi, L., Natta, A., et al., 2007, A&A469, 213

[24] Kley, W., D'Angelo, G., and Henning, T., 2001, ApJ 547, 457

[25] Kraus, A., and Ireland, M. 2012, ApJ 745, 5

[26] Lovelace, R. V. E.; Covey, K. R. and Lloyd, J. P., 2011, AJ 141, 51

[27] Lubow, S. H.; Seibert, M. and Artymowicz, P., 1999, ApJ 526, 1001

[28] Luhman, K.L., Adame, L., D'Alessio, P. et al., 2007, ApJ 666, 1219

[29] Macías, E., Anglada, G., Osorio, M. et al., 2016, ApJ 829, 1

[30] Oberg, K.I., Guzman, V., Furuya, K., et al., 2015, Nature 520, 148

[31] Oliveira, I., Pontoppidan, K.M., Merin, B. et al, 2010, ApJ 714, 778

[32] Pascucci, I., Apai, D., Luhman, K., et al., 2009, ApJ 696, 143

[33] Pietu, Guilloteau & Dutrey, A., 2005, A&A 443, 945

[34] Pietu, V., Guilloteau, S., Di Folco, E. et al., 2014, A&A 564, 95

[35] Pontoppidan, K.M., Blake, G.A., van Dishoeck, E.F. et al., 2008, ApJ 684, 1323

[36] Qi, Z., Oberg, K.I., Wilner, D.J., et al., 2013, Science 341, 630

[37] Qi, Z., Oberg, K.I., Andrews, S.M., et al. 2015. ApJ 813, 128

[38] Quanz, S., Amara, A., Meyer, M.R. et al. 2015, ApJ 807, 64

[39] Ribas, A., Bouy, H., Merin, B. et al., 2014, A&A 561, 54

[40] Ribas, A., Bouy, H. & Merin, B., 2015, A&A 576, 52

[41] Ricci, L., testi, L., Natta, A., et al., 2010, A&A 512, 15

[42] Ricci, L., Isella, A., Carpenter, J. et al., 2013, ApJ 764, 27

[43] Ricci, L., Testi, L., Natta, A. et al., 2014, ApJ 791, 20

[44] Sallum, S.; Follette, K. B.; Eisner, J. A et al., 2015, Nature 527, 342

[45] Protostars and Planets VI, H. Beuther, R.S. Klessen, C. P. Dullemond, and T. Henning (eds.), University of Arizona Press, Tucson, 914 pp., p.339-361

[46] Ubach, C.; Maddison, S. T.; Wright, C. M et al., 2012, MNRAS 425, 313

[47] van der Marel, N., van Dishoeck, E. F., Bruderer, S. et al., 2016, A&A585, 58

[48] Vicente, S.M. & Alves, J., A&A 441, 195

[49] Walsh, C., Loomis,R.A., Oberg, K.I. et al., 2016, ApJ 823, 10

[50] Whelan, E., Huélamo, N., Alcalá, J.M. et al., 2015, A&A 579, 48

[51] Williams, J. & Cieza, L., 2011, ARA&A 49, 67

[52] Wilner, D.J., D'Alessio, P., Calvet, N., et al., 2005, ApJ 626, 109

[53] Zapata, L., Rofriguez, L.F., Palau, A., 2016, ApJ, in-press