PROCEEDINGS OF SCIENCE

Modeling of the Disk around a Young, Isolated, Planetary-mass Object

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Even though the first observational evidence of the existence of isolated substellar objects dates from 1995, the heated debates surrounding these objects have not ceased. With masses below $\sim$0.072$M_{\odot}$ (and hence unable to sustain stable H burning, brown dwarfs, BDs) or even $\leq$13 M_{Jup} (and hence unable to sustain stable deuterium burning, isolated planetary mass objects, IPMOS), a number of theoretical conundrums have yet to be solved. From the dominant mechanism of formation, to the observational evidence that grain growth can occur during the first million years in the disks surrounding these extremely low-mass objects. In this work we present further analysis on the first detection in the millimetre range of the disk around OTS44 (one of the closest young IPMOS). This detection, possible thanks to the exquisite sensitivity of ALMA, allows us to conclude than grain growth has taken place in OTS44's disk and to further investigate the disk's properties via complete SED modeling.

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1. Introduction

Almost 25 years after the first detections of isolated substellar objects (Rebolo et al., 1995; Oppenheimer et al., 1995; Basri et al., 1996), and 55 years after the first models of their interiors (Kumar, 1963), the dominant mechanism of formation of such objects continues to provoke heated debates in the community. There is growing observational evidence that isolated substellar objects seem to pass through the same evolutionary status and phenomenology than stellar objects at ages of ∼1 Myr and older. These findings agree with substellar formation being "just" a scaled down version of low-mass star formation (Padoan & Nordlund, 2002; Hennebelle & Chabrier, 2008). However, updated competing theories (mostly: ejection, disk fragmentation, extremely eroding outflows, see respectively: Reipurth & Clarke 2001; Umbreit et al. 2005; Goodwin & Whitworth 2007; Stamatellos et al. 2007; Inutsuka & Miyama 1992) are nowadays also able to reproduce some of the observed phenomenology (accreting disks, outflows, some binary properties, etc), and the unambiguously detection of true pre and proto substellar objects is an ongoing quest even in the ALMA era (see André et al. 2012; Palau et al. 2012, among others).

Pushing even further the mass limit from the substellar border ($\sim$0.072$M_{\odot}$) to that of the stable deuterium burning one (the so called isolated planetary mass objects, IPMOS, with masses $\leq$13M_{Jup}), the picture becomes even more uncertain and the censuses in star forming regions are highly incomplete; making drawing any statistically robust conclusion an impossible task (see, among others, Bayo et al. 2011; Peña Ramírez et al. 2015; Mužić et al. 2015).

Even if "what is the dominant mechanism of formation for IPMOS?" is a question for which we do not have the data for an answer yet; this does not mean that other pressing problems related to IPMOS cannot be already addressed with the available instrumentation. For instance, both radial drift and fragmentation of solids, which are known problems in the formation of planetesimals in T-Tauri disks, are amplified for the physical conditions in brown dwarf or even IPMOS disks (Pinilla et al., 2013). Characterizing proto-planetary disks around the lowest mass objects thus provides key information for planet formation models.

2. OTS 44: one rare jewel

OTS44 is one of the lowest temperature member of the Chamaeleon I (Cha I) star forming region (spectral type estimated to be M9.5 or later). In principle, its mass has been estimated to be below or close to the planetary border (6-17M_{Jup}, Luhman et al. 2005; Bonnefoy et al. 2014). However, further assessment of these estimates need to be made after the reveal by Gaia DR2 of two possibly unrelated populations blurring the picture of what was considered until now a single Cha I population (Roccatagliata et al., 2018).

Given the young age of Cha I ($\leq$3Myr, Roccatagliata et al. 2018), it is not surprising that a large population of its members, still retain their optically thick disks. In particular, the first evidence for a disk around OTS44 came from mid- and far-IR excess emission detected with *Spitzer* and *Herschel* (Luhman et al., 2005; Harvey et al., 2012a,b).

Motivated by such detection and aiming at characterizing the disk-IPMO interaction, we observed OTS44 with VLT/SINFONI and detected strong, broad, and variable Pa β emission. We in-

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terpreted such detection as evidence for active disk accretion with a relatively high mass-accretion rate (8×10^{-12} $M_\odot$ yr^{-1}; Joergens et al. 2013).

OTS44 was also included in a large sample of brown dwarfs and IPMOS for which we compiled complete SEDs and modeled them with the radiative transfer code MC3D (Wolf, 2003) and a Bayesian analysis (Liu et al., 2015). The disk model that fitted the mid- and far-IR data best was that of a highly flared disk with a dust mass of $0.17M_\oplus$. However, the far-IR *Herschel* measurements (a detection at 70μm and an upper limit at 160μm) presented in that compilation, are, obviously, insensitive to millimeter-sized grains, with this potentially leading to an underestimation of the disk dust mass.

3. The ALMA detection

OTS 44 was observed with ALMA in Band 6 in Cycle 3. The full details of those observations, along with the continuum detection, are reported in Bayo et al. (2017), but in short, the object was unresolved (as expected) with a resolution of 1.6" $\times$ 1.6", and the peak flux value was 0.101 ± 0.01mJy (a solid detection given the 9.8μJy/beam RMS of the data).

In Bayo et al. (2017), we assumed that the millimeter emission was optically thin and isothermal at a given dust temperature. Then, exploring a range of temperatures and opacities, we estimated that the dust mass of the disk lies in the 0.07–0.63 $M_\oplus$ range (check Bayo et al. 2017 for further details).

In this work, we compare those values with those obtained from modeling the full SED with the addition of the new detection.

Additional observations of OTS44 are being carried out with ALMA in Cycles 5 and 6 (data still not fully delivered), but the modeling presented in this manuscript incorporates “only" the Cycle 3 observations (in the millimeter domain).

4. Disk mass via radiative transfer (RT) model of the full Spectral Energy Distribution (SED)

In order to model the full SED of OTS44, we used the RT code MC3D (Wolf, 2003) following the same strategy as in Joergens et al. (2013). In short, we model a 30^{o} inclined passive disk with spherical dust particles of astronomical silicate (62.5%) and graphite (37.5%) with a size range of $0.1\,\mu$m to $100\,\mu$m. For the dust we assume a density structure with a Gaussian vertical profile and a power-law distribution for the surface density. The outer disk radius $R_{\rm out}$ (in absent of resolved images) is set to 100 AU (compatible with the disk not being resolved in the Cycle 3 data), and to allow flaring, the scale height follows a power law with the flaring exponent β describing the extent of flaring and the scale height h_{100} at $R_{\rm out}$.

The SED fitting is performed with a hybrid strategy that combines the database method and the simulated annealing (SA) algorithm (Liu et al., 2013). The SED to be fitted is composed of our new ALMA flux and the photometry compiled in Joergens et al. (2013), with some variation in the *Spitzer/MIPS* 24 μm data for which we now take a weighted average of the two independent measurements provided in Luhman et al. (2008).

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The SED fitting results are shown in Fig. 1. In short, the best fitting model is characterized by a total dust mass of $0.27^{+0.36}_{-0.07}$ $M_\oplus$; an inner radius of $0.05^{+0.03}_{-0.04}$ AU; a flaring index of $1.24^{+0.04}_{-0.04}$; a scale height of 32^{+3}_{-7} AU (at 100 AU); and a mass-averaged dust temperature $\langle T_{\rm dust}\rangle = 11.9\,$K. Uncertainties correspond to the 68% confidence interval of the given parameter. A note of caution is that for these properties, the mass absorption coefficient at 1.3 mm, $\kappa_{1.3\rm mm}$, is 1.76 cm^{2}g^{-1} (as opposed to the 2.3 value used in Bayo et al. 2017). Using this 1.76 coefficient, the disk dust range of Bayo et al. (2017) would get revised to 0.09–0.82 $M_\oplus$ for the same dust temperatures range of 20 – 5.5 K.

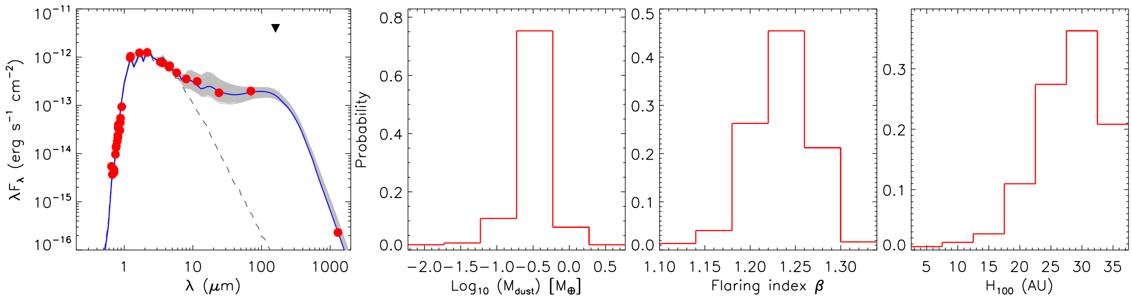

Figure 1: Left panel: Full SED of OTS44 from red-optical to the ALMA millimeter measurement (red dots; the black triangle represents the 160μm Herschel upper-limit) along with the assumed photosphere (dashed line), best fitting model (blue solid line), and the compatible family of models (grey solid lines). **Second, third and fourth panels:** Probability density functions of the three main parameters fitted: disk's dust mass, flaring index and scale height, respectively.

As mentioned in Sec. 2, by missing the contribution of the larger grains, our previous estimate for the disk's dust mass resulted in an under-estimation, but just by a factor ∼1.6. In addition, a model composed purely by interstellar-medium grain sizes (∼0.25μm), severely underestimates the millimeter flux (∼0.034mJy), hinting toward grain growth in such an extreme low-mass environment. More interestingly, the flaring index is now better constrained than in Joergens et al. (2013) and Liu et al. (2015), because we are sampling much better the probability density function of this parameter (see Fig. 1, third panel), and its value still contradicts the soft trend found in Liu et al. (2015), where the later the spectral type of the substellar object, the shallower the β index. As explained in Liu et al. (2015), the youth of OTS 44's disk suggests that dust settling has not yet proceeded very far. However, more very low-mass brown dwarfs and planetary-mass objects studied in the detail presented in this work are needed to reach any firm conclusions on this matter.

A caveat of the model just presented, is that no interstellar radiation field (IRF, perhaps a significant source for additional heating) is considered. Although neglecting the effect of IRF is the common practice in similar studies, we tested the impact that including the IRF as an external source of heating would have in a disk around such a cold central object. For this, we assumed the parametrization from Mathis et al. (1983) and included it in the radiative transfer code RADMC-3D[1] (C. P. Dullemond), which is prepared to consider external radiation fields. On the previously presented best fitting model, a first comparison was done between the results of running RADMC-3D and MC3D including just the central object radiation field. This comparison showed a very

[1]http://www.ita.uni-heidelberg.de/ dullemond/software/radmc-3d/

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good agreement with a difference in mass-averaged dust temperature of just ∼6%. Once the IRF is included, the differences in mass-averaged dust temperature reach the ∼10% level. This relatively small change in dust temperature introduced by the IRF affects the dust mass estimates to a lesser extent than, for example, the assumptions in mass absorption coefficients and their dependence with frequency.

Regarding comparisons with the literature we have gathered values from other substellar objects from van der Plas et al. (2016); Daemgen et al. (2016), where neither of these works consider the effects of IRF in their models. These comparisons are illustrated in Fig. 2. The sparse nature of the Figure, as well as the different assumptions involved in the modeling of the three studies (dust composition, etc.), preclude any conclusion further than a qualitative description stating that all measurements roughly follow a correlation with the mass of the central object.

5. Conclussions

In this work we present, to the best of our knowledge, the first thorough radiative transfer modeling (including interferometric millimeter data) of the disk around an IPMO (OTS44).

From this work, we can conclude that the effect of IRF is probably negligible in the mass estimate of the disk, in comparison with the uncertainties introduced by other factors such as mass absorption coefficients used (and their dependence with wavelength).

In addition to this result, we confirm with high significance (above 5σ) that grain growth must have happen in this disk: ISM like grains would translate in a predicted flux of 0.034 mJy as opposed to the 0.101±0.01 mJy detection. This poses an interesting challenge to theoretical work suggesting that radial drift (and hence inhibited grain growth) effects increases with decreasing mass of the central object (Pinilla et al., 2013).

Finally, the revised mid-infrared flux (see Bayo et al. 2017 for details) of OTS44 allows for better constraints (via SED fit) in the flaring index β. This newly constrained value suggest that dust settling has not yet proceeded very far in this young object.

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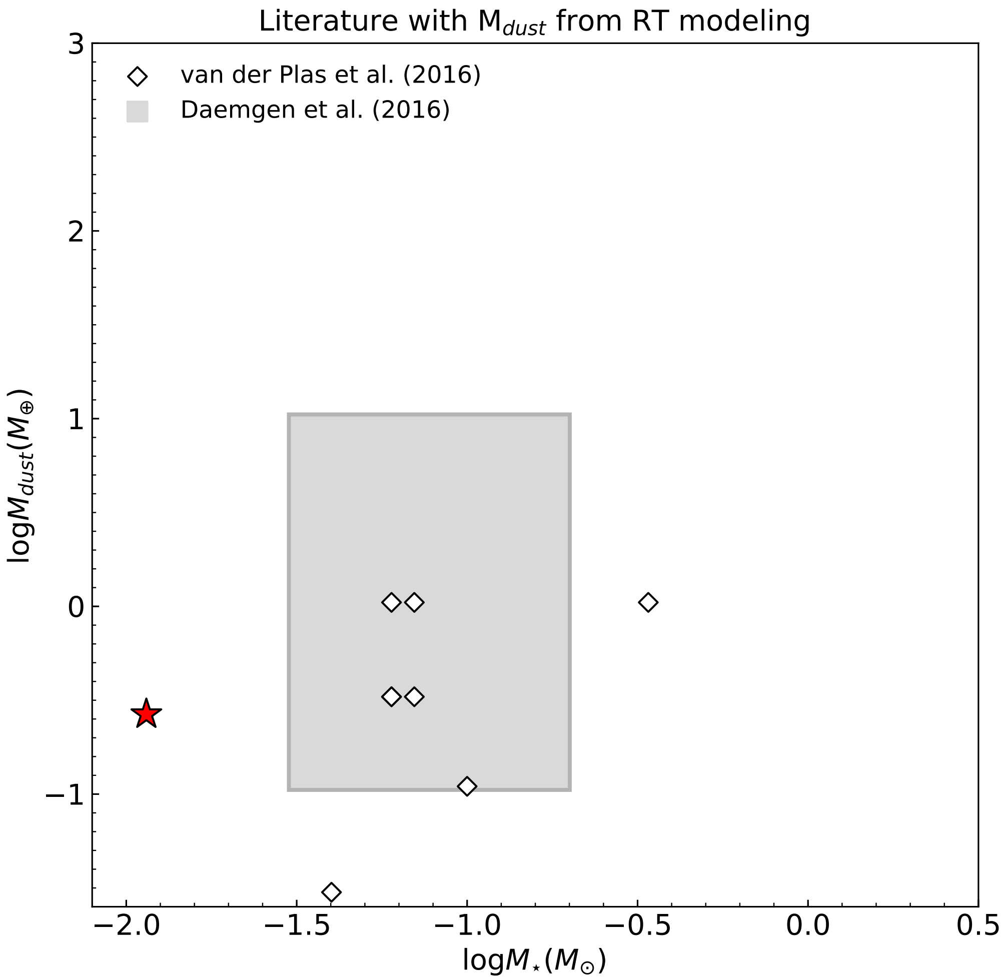

Figure 2: Comparison M_{dust} from RT modeling in the literature. The red five-point star shows the location of OTS44, and the grey box and open symbols the parameters studied / results from the works highlighted in the legend.

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DISCUSSION

J. H. BEALL: In the Cycle 5 ALMA data, will you try to resolve the source? if so, when will the observation occur?

A. BAYO: The aim of the ALMA Cycle 5 approved proposal is to resolve the disk spectroscopically in Band 7 and maybe (but we cannot guarantee it because it is model dependent) in the continuum in Band 9. We were not expecting to resolve it in the continuum in the Band 7 data given the similar spatial resolution with the Band 6 data (here presented), however, the Band 7 data already arrived and the object seems to be marginally resolved. We will have to wait to Cycle 6 for the Band 9 data because the project was passed to the next cycle not being completed in Cycle 5, but being re-awarded time.