(Sub)millimeter observations and disk modeling of substellar objects: understanding their formation processes

1 Abstract

How brown dwarfs (BDs) and even isolated planetary mass objects (IPMOs) form, is one of the main open questions in the field of star formation and remains a subject of debate until now. A scaled down version of star formation processes is one of the promising scenario. The circum-(sub)stellar disk serves as a crucial medium to understand their formation. Numerous observations of BDs in recent years have detected disks with properties similar to those found in T Tauri stars, suggesting that BDs may form in a similar way to hydrogen-burning stars. Despite this progress, thorough disk comparisons are required to obtain a clear view of the formation mechanism of BDs and IPMOs.

OTS 44 is one of the only four free-floating planets known to have a disk and the only one detected in the millimeter regime. Recently, we analyzed ALMA, Cycle 3, band 6 (1.3 mm) continuum data and found that the disk dust mass is in the range of $0.07-0.63\,M_{\oplus}$, suggesting that the scaling relation between disk and stellar masses found for larger mass central objects holds down to planetary masses (Bayo et al. 2017). This hints toward OTS 44 forming in a similar way to hydrogen-burning stars. However, the estimates of the masses of the disk and the central object are subject to huge uncertainties and bold assumptions. We have been granted a Cycle 5, ALMA proposal (PI Bayo, ranked B) to derive the dynamical mass of the central object (for the first time a model-independent mass estimate for such object) by spectroscopically resolving the gas content of the disk. We will also place better constraints on the disks dust mass and directly test grain growth via the spectral index provided by the new data. In addition, we have obtained high resolution optical and near-infrarred spectroscopy of members of the same star forming region, Chamaeleon I, that could have been associated with OTS44 during its formation. The wealth of data for OTS 44 needs to be properly modeled in order to compare the disks around substellar objects with those around stellar ones to search for similarities and/or differences (disk size, geometry, etc.) that will shed light over the formation mechanism of isolated substellar objects.

Pending the results of the Cycle 5 successful observations; as a backup project, we plan to analyze the already collected ALMA and APEX data on Barnard 35 dark cloud. This dark cloud is part of the Lambda Orionis Star forming region (LOSFR, that has been subject of study by the PI Bayo since my PhD thesis) and has an estimated age of ∼3 Myr (Bayo et al. PhD, among others). The science case behind the gathering of this secondary dataset is closely related to the case of OTS 44 but for somewhat higher masses (still in the substellar domain).

2 Chilean project proposer

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3 Scientific justification

Molecular cloud fragmentation is accepted as the initial step on the formation of low-mass stars, but since the typical Jean mass of molecular clouds is $\sim 1\,M_\odot$, objects below the Hydrogen-burning limit ($\sim 0.072\,M_\odot$) cannot form as a scaled-down version of the former. Several scenarios are proposed in the literature to overcome this caveat either invoking new mechanisms like dynamical interactions (Reipurth & Clarke 2001), massive-disks fragmentation (Goodwin & Whitworth 2007; Stamatellos et al. 2007), or photoevaporation (Whitworth & Zinnecker 2004), or modifying the initial conditions introducing turbulence so that the Jeans mass decreases (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008).

Similar to their higher mass counterparts, such as T Tauri stars, young BDs are shown to have circumstellar disks, producing substantial excess emission (e.g., Scholz et al. 2006; Bayo et al. 2012; Harvey et al. 2012; Liu et al. 2015a). Disks are also found around very faint objects with masses down to the planetary regime, for example LOri 156 ($\sim 23\,M_{\rm Jup}$, Bayo et al. 2012) and OTS 44 ($\sim 12\,M_{\rm Jup}$, Luhman et al. 2005; Joergens et al. 2013). The phenomena of mass accretion and outflow, which are common by-products of the star formation process, have also been detected in young BDs (e.g., Mohanty et al. 2005; Phan-Bao et al. 2008; Joergens et al. 2012) even down to the planetary mass regime (e.g., Bayo et al. 2012; Joergens et al. 2013). The dust evolution in BD disks appears to follow a similar manner (i.e., grain growth, settling and crystallization) to that in T Tauri disks, although observations suggest different timescales of dust processing in disks around different stellar mass hosts (e.g., Apai et al. 2005; Bouy et al. 2008; Pascucci et al. 2009). These observations show that BDs resemble hydrogen-burning stars in many aspects during their early evolution, implying that they may form through the canonical star formation processes.

The relationship between disk and stellar properties provides important clues about the formation mechanism of BDs. In an earlier work, we modeled the spectral energy distributions a sample of 55 BDs and very low mass stars and found that the dependence of disk geometry on the mass of the central object is valid within the substellar regime (Liu et al. 2015b). However, the sample of this study is established from different star formation regions and is biased towards low mass BDs. Therefore, more thorough disk comparisons are required to shed light on substellar formation processes.

4 Implementation

4.1 Main project:

We have conducted a series of studies on OTS 44, which is a young, isolated, planetary-mass object located in the Chamaeleon I star formation region (Joergens et al. 2013; Liu et al. 2015b; Bayo et al. 2017). The results suggested a stellar-like gravitational collapse of a dense (sub)stellar core as the most plausible mechanism to form this interesting object (see Figure 1). However, this notion has to be further tested because currently there is no information about the disk size and grain size distribution, and the estimate of the mass of the central object is still model-dependent. Following up our previous works, we submitted and were awarded (ranked B) a Cycle 5, ALMA proposal to observe OTS 44 at band 7 and 9. With these data we aim at spatially resolving the dust continuum at band 7 and detecting the dust emission at band 9. Finally, spectrally resolved CO (3−2) data will be obtained by the proposed band 7 observation as well.

We will reduce the new ALMA data from which a wealth of new information on the disk and (sub)stellar properties can be directly obtained. There is so far no constraints on the disk size, incli-

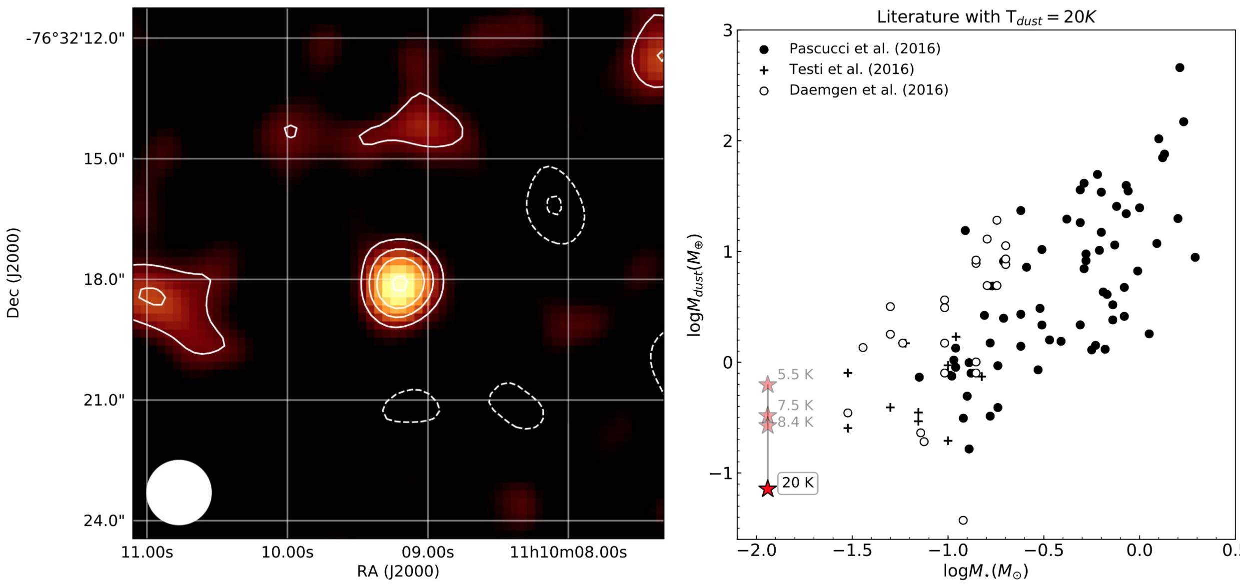

Figure 1: *Left panel:* Non-resolved 1.3 mm detection of the disk around OTS 44 with our ALMA Cycle 3, band 6 data. The beam size is shown on the bottom left of the image (Bayo et al. 2017). *Right panel:* The relationship between the disk dust mass (in earth masses) and the mass of the central object (in solar masses) for very low-mass objects. The planetary mass object, OTS 44, is displayed as 4 stars (assuming 4 different dust temperatures in the derivation of the disk dust mass) connected by a black line. Note the agreement of the dust mass of the disk around OTS 44 with the relationship derived from the higher-mass objects studied in the literature (Bayo et al. 2017).

nation and position angle. We will derive these quantities from the spatially resolved observation at band 7. We will measure the (sub)millimeter spectral index α between 0.45 mm (band 9) and 1.3 mm (band 6) and convert it into the opacity index β of the dust emissivity coefficient ($\kappa_\nu \propto \nu^\beta$, $\beta = \alpha - 2$). Whether grain growth occurs in such an extreme environment can be testified for small values of $\beta < 1$ (e.g., Testi et al. 2014; Pérez et al. 2015). In order to quantitatively analyze the physical structure of the disk and the dust properties, we plan to build a self-consistent radiative transfer model that can explain the SED (with a better wavelength coverage), the spatially resolved visibilities and the CO (3−2) gas emission line, simultaneously. We will explore the parameter space for the disk structure, the grain size distribution and for the CO gas mass in the modeling. In addition, a Bayesian analysis will be performed to evaluate the constraints on each parameter. We will determine the characteristic temperature of the dust from the models within the confidence interval. The inferred disk properties of OTS 44 will be compared to those found for higher-mass objects like BDs and T Tauri stars. We will search for similarities or differences between them, which yields important insights into the formation mechanism of isolated BDs and even for planetary mass objects.

On the other hand, with the new ALMA data, we will also be able to infer a dynamic mass of the central object if the Keplerian rotation for the CO gas emission is detected. Such a mass estimate is model-independent. We have previously estimated model dependent masses (based on ancillary data: IMACS/Magellan I (Luhman 2007) and VLT/SINFONI spectra (Joergens et al. 2013)).We will thus be able to check the consistency between the masses inferred with these two methods. A strong constraint on the mass of the central object tells us the minimum mass that the canonical star formation process can produce, which is the key to understanding star and BD formation.

Finally, we will discuss the implications of our findings on models of solids evolution in protoplanetary disks, the scaled-down version of star formation processes as the mechanism proposed for the formation of BDs and even planetary mass objects, as well as the potential of finding giant planets around very low-mass objects.

4.2 Backup project:

The working plan will comprehend the detailed data reduction of the APEX and ALMA data on Barnard 35 dark cloud (preliminary reduction carried out by the PI shows three very interesting sources, one of them being a transitional disk and two proto-stellar/brown dwarf sources). Identification of additional interesting candidates with lower signal-to-noise ratios. Radiative transfer modeling of the full SEDs of the candidates plus comparison of the main parameters obtained via empirical relationships, and analysis of the dependence of the estimated parameters with the environment. The latter will be achieved via consistent comparison with the objects identified with relatively similar data in Taurus and Barnard 30 (and by other groups in Ophiucus, for example). Finally, a Cycle 6 ALMA proposal will be submitted to analyze, at high angular resolution, the most promising candidates to pre-substellar cores, proto-brown dwarfs, and young disks around substellar central objects.

5 China-Chile connection

I have a recent collaboration with Prof. Hongchi Wang from Purple Mountain observatory via his former student and now postdoctoral researcher Dr. Yao Liu. The present project could help strengthen that collaboration by following similar methodologies than in Liu et al. (2015b), where the potential of the observational data available in Valparaíso could be fully exploited, simulation and modeling-wise, with the GPU cluster (installed with 450 CPUs) at Purple Mountain Observatory.

6 Project duration

The project consists on the analysis of a very large and inhomogeneous observational database and requires a large amount of simulation, therefore, we expect to finish it in three years.

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