OTA 44: Disk and accretion at the planetary border*,**

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ABSTRACT

We discover that the very low-mass brown dwarf OTS 44 (M9.5, ~12 MJ) has significant accretion and a substantial disk, which demonstrates that processes that accompany canonical star formation occur down to a central mass of a few Jupiter masses. We discover in VLT/SINFONI spectra of OTS 44 strong, broad, and variable Paβ emission that is evidence for active accretion on the planetary border. We also detect strong Hα emission of OTS 44 in a literature spectrum and determine an Hα EW of ~141 Å, which indicates active accretion. Both the Paβ and Hα emission lines have broad profiles with wings extending to velocities of about ±200 km s−1. We determine the mass accretion rate of OTS 44 based on Hα to 7.6 × 10−12 Ms−1 yr−1. This result shows that OTS 44 has a relatively high mass-accretion rate considering its small central mass. This mass rate is nevertheless consistent with the general decreasing trend found for stars of several solar masses down to brown dwarfs. Furthermore, we determine the properties of the disk surrounding OTS 44 through radiative transfer modeling of flux measurement from the optical to the far-IR (Herschel) by applying a Bayesian analysis. We find that OTS 44 has a highly flared disk (β ≳ 1.2) with a mass of 9.1 ± 1.7 × 10−5 Ms−1, i.e., ~0.1 MJ or 30 MJearth. We show that the ratio of the disk-to-central-mass of about 10−2 found for objects between 0.03 Ms and 14 Ms is also valid for OTS 44 at a mass of ~0.01 Ms. Our observations are in line with an isolated star-like mode of the formation of brown dwarfs down to 0.01 Ms.

Key words. brown dwarfs – stars: pre-main sequence – circumstellar matter – accretion, accretion disks – stars: formation – stars: individual: OTS 44

1. Introduction

One of the main open questions in the theory of star formation is: How do brown dwarfs form? A high-density phase is necessary for the gravitational fragmentation to create very small Jeans-unstable cores. Proposed scenarios to prevent a sub-stellar core in a dense environment from accreting to stellar mass are (i) ejection of the core through dynamical interactions; (ii) photo-evaporation of the gas envelope through radiation of a nearby hot star; and (iii) disk instabilities in circumstellar disks. Alternatively, brown dwarfs could form in an isolated mode by direct collapse. For example, filament collapse (e.g., Inutsuka & Miyama 1992) might form low-mass cores that experience high self-evaporation in outflows and become brown dwarfs (Machida et al. 2009). A key to understanding star and brown dwarf formation is to observationally define the minimum mass that the star formation process can produce by detecting and exploring the main features characteristic of star formation, such as disks, accretion, and outflows, for very low-mass objects.

Young brown dwarfs were shown to have substantial circumstellar disks at far-IR and mm wavelengths (e.g., Harvey et al. 2012; Ricci et al. 2013). Many of these brown dwarfs were found to actively accrete material through the disk onto the central object (e.g., Rigliaco et al. 2012), and a handful of them also to drive outflows (e.g., Whelan et al. 2005; Phan-Bao et al. 2008; Bacciotti et al. 2011; Joergens et al. 2012a,b; Monin et al. 2013). Among the lowest-mass isolated objects found to harbor a disk are Cha 110913-773444 (~8 MJ, Luhman et al. 2005a), LOr1 156 (~23 MJ, Bayo et al. 2012), and OTS 44 (~12 MJ, Luhman et al. 2005b).

OTS 44, which is the subject of the present work, was first identified as a brown dwarf candidate in a deep near-IR Imaging survey in the Chamaeleon I star-forming region (Oasa et al. 1999). It was confirmed to be a very low-mass brown dwarf of spectral-type M9.5 with an estimated mass of ~15 MJ based on low-resolution near-IR and optical spectra (Luhman et al. 2004; Luhman 2007). Bonnefoy et al. (2013) recently confirmed in a near-IR study a mass in the planetary regime (~6–17 MJ). Mid- and far-IR excess emission detected with Spitzer (Luhman et al. 2005b) and Herschel (Harvey et al. 2012) indicated that OTS 44 has a disk. We present SINFONI / VLT spectroscopy of OTS 44 that reveals strong Paschenβ emission, an analysis of Hα emission in a spectrum from Luhman (2007), and a detailed modeling of the spectral energy distribution (SED) of the disk of OTS 44 based on Herschel data.

2. Observations

The spectral energy distribution. To model the disk and photosphere of OTS 44, we compiled optical to far-IR flux measurements from the literature. In the optical, we use I-band data from

* Based on observations at the Very Large Telescope of the European Southern Observatory at Paranal, Chile in program 80.C-0590(A).
** Appendix A is available in electronic form at http://www.aanda.org
Luhman et al. (2005b) and an R-band magnitude of 23.5 ± 0.1 (Luhman, priv. comm.). The near-IR (JHK) regime is covered by observations of 2MASS and WISE. We note that the WISE W4 photometry of OTS 44 was not used because of contamination by a bright spike. Mid-IR photometry of OTS44 was obtained by Spitzer using IRAC (3.6, 4.5, 5.8, 8.0 μm) and MIPS (24, 70, 160 μm, Luhman et al. 2008). Recently, OTS 44 was observed in the far-IR (70, 160 μm) by Herschel/PACS (Harvey et al. 2012).

Near-infrared SINFONI integral field spectroscopy. We observed OTS 44 with the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) at the VLT on December 14 and 21, 2007. The observations were conducted as part of a program designed to provide a library of near-IR spectra of young late-type objects (Bonnefoy et al. 2013). The instrument was operated with pre-optics and gratings enabling medium-resolution (R = λ/Δλ ~ 2000) J-band spectroscopy (1.1–1.4 μm) with a spatial sampling of 125 × 250 mas/pixel. We reduced the data with the SINFONI data reduction pipeline version 1.9.8 and custom routines (cf. Bonnefoy et al. 2013, for details). The pipeline reconstructs datacubes with a field of view of 1.125 × 1.150″ from bi-dimensional raw frames. Telluric absorptions features were calibrated and removed based on the observations of B5V stars. The wavelength calibration based on arc lamp spectra has an accuracy of about 30 km s⁻¹. The wavelength calibration throughout the paper, which is the average radial velocity of T Tauri stars and brown dwarfs in Châtaignier (2006).

Optical spectroscopy. An optical spectrum covering the range 0.5–1 μm with a resolution R = 900 was taken by Luhman (2007) with IMACS at the Magellan I telescope on January 6, 2005. This spectrum is used to analyze the Hα emission of OTS 44 and to provide an additional constraint to the photosphere model fit. We calculate the heliocentric radial velocities relative to V₀.

3. Photospheric properties of OTS 44

We find that it is not possible to fit the SED of OTS 44 when using the properties reported for this brown dwarf in the literature (Teff = 2300 K, L∗ = 0.0007 L⊙, Av = 0, Luhman 2007). Therefore, we performed a thorough modeling of the photosphere of OTS 44 by applying the BT-Settl models (Allard et al. 2012). These models incorporate a sophisticated treatment of photospheric dust, which is likely to affect the cool atmosphere of OTS 44. We use broadband photometry, a narrow grid of flux points calculated from the optical spectrum (Luhman 2007), and a surface gravity log(ν) of 3.5, as determined from gravity-sensitive lines (Bonnefoy et al. 2013). We derive an effective temperature of Teff = 1700 K, a luminosity of L∗ = 0.0024 L⊙, and an extinction of Av = 2.6 mag (Table 1). Bonnefoy et al. (2013) also found indications for a lower Teff of OTS 44. The probability distributions of the parameter values in our modeling approach are relatively broad, which hints at a remaining discrepancy with the models. We conclude that the photospheric properties of OTS 44 may still need to be refined in the future.

4. SED modeling of the disk of OTS 44

We model the SED of OTS 44 using the radiative transfer code HiC3D (Wolf 2003) to characterize its circumstellar environment. Because the disk parameters are strongly degenerate in the fitting procedure, we employ a passive-disk model consisting of a central substellar source surrounded by a parametrized disk.

Dust distribution in the disk. We introduce a parametrized flared disk in which dust and gas are well mixed and homogeneous throughout the system. This model has been successfully used to explain the observed SEDs of a large sample of young stars and brown dwarfs (e.g., Wolf et al. 2003; Harvey et al. 2012). For the dust in the disk we assume a density structure with a Gaussian vertical profile ρdust = ρ0(R/σ)d exp(−z²/2σ²(σ)), and a power-law distribution for the surface density Σd = Σ0(R/σ)d, where σ is the radial distance from the central star measured in the disk midplane, and h(σ) is the scale height of the disk. The outer disk radius Rout is set to 100 AU. To allow flaring, the scale height follows the power law h(σ) = h100(σ/100 AU)0.5, with the flaring exponent β describing the extent of flaring and the scale height h100 at Rout.

Dust properties. We consider the dust grains to be homogeneously distributed, which is a valid approximation to describe the scattering behavior as compared to a more complex description with fractal grain structures. The dust grain ensemble incorporates both astronomical silicate (62.5%) and graphite (37.5%) material. The grain size distribution is given by the standard power law n(σ) ∝ σ⁻³.₅ with minimum and maximum grain sizes of 0.005 μm and 0.25 μm, respectively.

Heating sources. We consider a passive disc with only stellar irradiation, but no viscous heating (e.g., Chiang & Goldreich 1997). Radiation heating of the dust from the accretion luminosity can be neglected because Lacc < 0.2% L∗ (Sect. 5). For Teff and L∗ of the central source, we use the values derived here (Table 1, set 2) and ḷ = 162.5 pc. As said, an SED model using the parameters from Luhman (2007; set 1 in Table 1) cannot reproduce the observations. The incident substellar spectrum is taken from the BT-Settl atmosphere database with log(ν) = 3.5 (Allard et al. 2012). The radiative transfer problem is solved self-consistently considering 100 wavelengths, logarithmically distributed in the range of [0.05 μm, 2000 μm].

Fitting results. The SED fitting is performed with a hybrid strategy that combines the database method and the simulated
Table 2. Disk parameter values of the best-fit SED model.

<table>
<thead>
<tr>
<th>$R_{in}$</th>
<th>$R_{out}$</th>
<th>$p$</th>
<th>$\beta$</th>
<th>$h_{100}$</th>
<th>$m_{disk}$</th>
<th>$m_{disk}'$</th>
<th>$i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[AU]</td>
<td>[AU]</td>
<td></td>
<td></td>
<td>[AU]</td>
<td>[$10^{-5} M_{\odot}$]</td>
<td>[$M_{\odot}$]</td>
<td>['']</td>
</tr>
<tr>
<td>0.023</td>
<td>100</td>
<td>1.136</td>
<td>1.317</td>
<td>17.42</td>
<td>9.06</td>
<td>30.2</td>
<td>58</td>
</tr>
</tbody>
</table>

Notes. For the photosphere, the values of set 2 of Table 1 were used. See Sect. A for confidence intervals of the disk parameters.

annealing (SA) algorithm (Liu et al. 2013). We first run a large grid of disk models with a broad range of disk parameters. Then SA is used to improve upon the results returned by the model grid and to calculate local confidence intervals. The best-fit model is shown in Fig. 1 and the corresponding disk parameter values are listed in Table 2. The best-fit model is not a unique solution due to model degeneracies between different parameters, for example $m_{disk}/R_{out}$. We therefore conduct a Bayesian analysis to estimate the validity range for each parameter (Pinte et al. 2008). We find that the best-fit and the most probable values (cf. Sect. A) agree well with each other, in particular the disk parameters.

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5. Paschen$\beta$ and H$\alpha$ emission

We discover a strong and broad Paschen$\beta$ (Pa$\beta$) emission line in our near-IR SINFONI spectra of OTS 44 (Fig. 2). Furthermore, a prominent H$\alpha$ emission line is visible in the optical spectrum of Luhman (2007, see Fig. 2). Both of these Hydrogen emission lines exhibit a broad profile with velocities of $\pm 200\,\text{km}\,\text{s}^{-1}$ or more. We investigate the properties and origin of these lines through a line profile analysis. We determine the equivalent width (EW) by directly integrating the flux within the line region and the EW errors following Sembach & Savage (1992).

Furthermore, we measure the line center and full width at half maximum (FWHM) based on a Gaussian fit to the profiles. Table 3 lists the results.

The H$\alpha$ line has a symmetrically shaped profile with an EW of $-141\,\text{Å}$, demonstrating that OTS 44 is actively accreting (e.g. Barrado & Martin 2003). The line appears to be blueshifted with its center located at $-30\,\text{km}\,\text{s}^{-1}$. Higher resolution spectroscopy is needed to determine whether this shift is real.

The shape of the Pa$\beta$ line appears to be slightly asymmetric, with the red wing being more pronounced. The profile is significantly variable between the two observing epochs separated by a few days. We measure an EW of $-6.7$ and $-4.2\,\text{Å}$ for the spectra from December 14 and 21, respectively. The line has a peak at redshifted velocities at about $40-50\,\text{km}\,\text{s}^{-1}$. We see a redshift of similar order also in photospheric lines of OTS 44. While the Pa$\beta$ emission of T Tauri stars is mostly attributed to magnetospheric accretion and winds (e.g., Rigliaco et al. 2012), there is observational evidence that part of the Pa$\beta$ emission, in particular the broad line wings, can be formed by other processes, such as outflows (e.g., Whelan et al. 2004). We conducted

![Fig. 2. Pa$\beta$ emission of OTS 44 in SINFONI/VLT spectra and H$\alpha$ emission of OTS 44 based on a spectrum from Luhman (2007). The dashed lines are Gaussian fits to the profiles.](Image)

6. Conclusions

We have discovered strong, broad, and variable Pa$\beta$ emission of the young very low-mass brown dwarf OTS 44 (M9.5) in VLT/SINFONI spectra, which is evidence for active accretion
at the planetary border. We determined the properties of the disk that surrounds OTS 44 through MC3D radiative transfer modeling of flux measurements from the optical to the far-IR (Herschel). We found that OTS 44 has a highly flared disk ($\beta > 1.2$) with a mass of $9.1^{+1.7}_{-1.5} \times 10^{-3} M_\odot$, i.e. about $0.1 M_\text{up}$ or $30 M_\text{Earth}$. We also investigated the Hα line of OTS 44 in a spectrum from Luhman (2007) and found strong Hα emission with an EW of $-141 \, \AA$ indicative of active accretion. Both the Paβ and Hα emission lines of OTS 44 have broad profiles with the wings extending to velocities of about $\pm 200 \, \text{km s}^{-1}$. The Paβ emission is significantly variable on timescales of a few days, indicating variability in accretion-related processes of OTS 44. We estimated the mass accretion rate of OTS 44 to $7.6^{+6.4}_{-4.0} \times 10^{-12} M_\odot \, \text{yr}^{-1}$ by using the Hα line. A mass accretion rate based on the Paβ line gives a significantly higher value, and we speculate that part of the Paβ emission might come from other processes related to accretion, such as outflows. Furthermore, in the course of studying OTS 44, we fitted a photospheric BT-Settl model to its optical and near-IR SED and derived a lower effective temperature and higher extinction than was previously found (Luhman 2007).

We have presented the first detection of Paβ emission for an object at the deuterium-burning limit. Our analysis of Paβ and Hα emission of OTS 44 demonstrates that objects of a few Jupiter masses can be active accretors. Furthermore, OTS 44 is the lowest-mass object to date for which the disk mass is determined based on far-IR data. Our detections therefore extend the exploration of disks and accretion during the T Tauri phase down to the planetary mass regime. Plotting the relative disk masses of stars and brown dwarfs including OTS 44 (Fig. 3) shows that the ratio of the disk-to-central-mass of about $10^{-2}$ found for objects between $0.03 M_\odot$ and $14 M_\odot$ is also valid for OTS 44 at a mass of about $0.01 M_\odot$. Furthermore, the mass accretion rate of OTS 44 is consistent with a decreasing trend from stars of several solar masses to brown dwarfs down to $0.01 M_\odot$ (Fig. 4). It is also obvious from this figure that OTS 44 has a relatively high mass accretion rate considering its small mass. These observations show that the processes that accompany canonical star formation, disks and accretion, are present down to a central mass of a few Jupiter masses. OTS 44 plays a key role in the study of disk evolution and accretion at an extremely low mass and, therefore, in constraining the minimum mass that star formation can produce. It will be the target of our future observational efforts.

**Fig. 3.** Relative disk mass versus central mass of stars and brown dwarfs including OTS 44 (red diamond). We note that for $\mu$Oph102 we use $M_* = 0.13 M_\odot$ (M5.5, Luhman, priv. comm.), different from Ricci et al. (2012, 0.06 $M_\odot$).

**Fig. 4.** Mass accretion rate versus central mass of stars and brown dwarfs including OTS 44 (red diamond).

**Acknowledgements.** We thank K. Luhman for providing the optical spectrum of OTS 44 and related information, C. Dumas and A.-M. Lagrange for help with the SINFONI data reduction, the ESO staff at Paranal for executing the SINFONI observations in service mode, and the anonymous referee for very helpful comments. This work made use of the NIST database (Kramida et al. 2012) and VOSA (Bayo et al. 2008). MB acknowledges funding from Agence Nationale pour la Recherche, France through grant ANR10-BLANC0504-01.

**References**


Appendix A: Bayesian probability analysis

Fig. A.1. Bayesian probability distributions of selected disk parameters.

Table A.1. Confidence intervals of the disk parameter values of OTS 44.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best model</th>
<th>Valid range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{in}$ [AU]</td>
<td>0.023$^{+0.018}_{-0.013}$</td>
<td>0.01–0.04</td>
</tr>
<tr>
<td>$R_{out}$ [AU]</td>
<td>100</td>
<td>fixed</td>
</tr>
<tr>
<td>$p$</td>
<td>1.136$^{+0.051}_{-0.023}$</td>
<td>0.62–1.27</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.317$^{+0.017}_{-0.042}$</td>
<td>1.16–1.32</td>
</tr>
<tr>
<td>$h_{100}$ [AU]</td>
<td>17.42$^{+6.68}_{-2.55}$</td>
<td>9.0–18.5</td>
</tr>
<tr>
<td>$m_{disk}$ [$10^{-5}M_\odot$]</td>
<td>9.06$^{+1.72}_{-0.46}$</td>
<td>0.32–56.2</td>
</tr>
<tr>
<td>$i$ [$^\circ$]</td>
<td>58$^{+6}_{-9}$</td>
<td>18–65</td>
</tr>
</tbody>
</table>

Notes. Parameter values of the best-fit SED model with local errors and the valid ranges for each parameter. The local error is deduced based on simulated annealing by probing the direct environment of the best fit with a Markov chain. The valid range for each parameter gives a 68% confidence interval based on the Bayesian probability distribution, as shown in Fig. A.1.