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FIRST DETECTION OF MILLIMETER DUST EMISSION FROM BROWN DWARF DISKS

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ABSTRACT

We report results from the first deep millimeter continuum survey targeting brown dwarfs (BDs). The survey led to the first detection of cold dust in the disks around two young BDs (CFHT-BD-Tau 4 and IC 348 613), with deep JCMT and IRAM observations reaching flux levels of a few microjanskys. The dust masses are estimated to be a few Earth masses, assuming the same dust opacities as are usually applied to T Tauri stars.

Subject headings: accretion, accretion disks — circumstellar matter — stars: formation — stars: individual (CFHT-BD-Tau 4, IC 348 613) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Several near-infrared surveys (Muench et al. 2001; Oliveira et al. 2002; Liu, Najita, & Tokunaga 2003; Jayawardhana et al. 2003) and mid-infrared measurements (Comerón, Neuhäuser, & Kaas 2000; Persi et al. 2000; Testi et al. 2002; Natta et al. 2002; Apai et al. 2002) indicate the presence of disks around brown dwarfs (BDs). In contrast to infrared emission, submillimeter emission and millimeter emission are certainly always optically thin and are excellent measures for the total dust mass.

An early attempt was made by Andre & Montmerle (1994) to detect millimeter continuum emission from very low mass stars and suspected BDs. Probably the most sensitive observation of this kind was carried out by Carpenter (2002) using the Owens Valley Observatory (OVRO) interferometer, although at a relatively long wavelength. We carried out the first successful search for dust continuum emission associated with confirmed BDs, using the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) and the Max-Planck Millimeter Bolometer (MAMBO) array on the IRAM 30 m telescope.

The survey led to the detection of circumstellar dust around the two young BDs CFHT-BD-Tau 4 and IC 348 613, which have ages below 10 Myr. In the case of field BDs, we obtained upper mass limits of a few Moon masses of dust. For BDs in the Pleiades, the mass limits are less strict and range from 4 to 7 Earth masses (M_E). We should note that the data presented for CFHT-BD-Tau 4, together with other ground-based and *Infrared Space Observatory* data, allowed us to have the first detailed discussion of a complete spectral energy distribution of a BD, ranging from optical to millimeter wavelengths (Pascucci et al. 2003).

The detection of these amounts of circumstellar material around two young BDs makes the formation of planets or even planetary systems around BDs a possibility. Therefore, search strategies for planets should include BDs. In the case of imaging surveys, they might even be the best targets.

In addition, the detection of significant amounts of circumstellar dust also provides us with important information about the formation processes of BDs. These detections, together with the discovery of quite a number of BD binaries (Bouy et al. 2003; Burgasser et al. 2003), do not support the fragmentation of circumstellar disks as the general process for BD formation. Other formation scenarios for BDs (Bate, Bonnell, & Bromm 2003; Reipurth & Clarke 2001; Watkins et al. 1998) include ejection from multiple systems and erosion of star-forming cloudlets by stellar winds and UV radiation from massive stars. Disks will certainly have different structures depending on the formation mechanism. However, the statistics is still poor, and information about the disk structure from interferometric observations is needed before one can put more definite observational constraints on BD formation scenarios.

2. OBSERVATIONS

To search for circumstellar material around BDs, we selected relatively young BDs with ages of a few megayears because these objects should have the highest probability of being associated with disk material. The nine selected objects are located in Taurus, the σ Orionis cluster, IC 348, and the Upper Scorpius OB association (Martín et al. 2001; Béjar et al. 2001; Najita, Tiede, & Carr 2000; Luhman 1999; Ardila, Martín, & Basri 2000). For the first three regions, additional selection criteria were the previous detection of Hα emission (Martín et al. 2001), the presence of X-ray emission (Mokler & Stelzer 2002; Preibisch & Zinnecker 2001), and the requirement that the objects should be as isolated as possible in order to avoid confusion during the observations with single-dish telescopes.

The three BDs in the Taurus star-forming region are among the youngest BDs of our target list. They have ages of about 1 Myr (Martín et al. 2001). The object CFHT-BD-Tau 4 shows the highest Hα emission among the Taurus BDs (Martín et al. 2001), emits X-radiation (Mokler & Stelzer 2002), and shows mid-infrared excess emission (Pascucci et al. 2003).

The second group that we selected consists of objects in the Pleiades that have distances of 116 pc and ages of 0.12 Gyr. The objects are considerably older than the first group of BDs. In addition, we searched for dust emission from very nearby field BDs. On the average, these objects are older than the first group too, but the actual age determination contains large uncertainties.

TABLE 1
TARGET LIST

Target	R.A. (2000)	Decl. (2000)	Distance (pc)	Age (Myr)	References
BDs in Taurus			140	1	1
CFHT-BD-Tau 1	04 34 15.2	+22 50 31			
CFHT-BD-Tau 2	04 36 10.4	+22 59 56			
CFHT-BD-Tau 4	04 39 47.3	+26 01 39			2
BD in σ Ori cluster			370	1	3, 4
S Ori 03	05 39 20.8	−02 30 35			
BD in IC 348			260	0.5–10	5, 6
IC 348 613	03 44 26.9	+32 09 24.8			
BDs in Upper Scorpius			145	5	7, 8, 9
U Sco 100	16 02 04.13	−20 50 41.5			
U Sco 104	15 57 12.66	−23 43 45.3			
U Sco 112	16 00 26.57	−20 56 32.0			
U Sco 128	15 59 11.20	−23 37 59.0			
BDs in the Pleiades			116	120	10, 11, 12
NPL 36	03 48 19.1	+24 25 15			
NPL 37	03 47 12.1	+24 28 31			
NPL 38	03 47 50.4	+23 54 49			
NPL 30 (Teide 1)	03 47 17.9	+24 22 32			
Field BDs				$\gtrsim$100[a]	
Gl 229B	06 10 35.1	−21 51 18	5.8	500	13, 14, 15
2MASSI J0746425+200032[b]	07 46 42.5	+20 00 32	12.3	…	16, 17
2MASSI J0825196+211552	08 25 19.6	+21 15 52	12.5	…	16, 17
LHS 2397a[c,d]	11 21 49.3	−13 13 09	14.2	2–12 Gyr	17, 18, 19, 20
Kelu 1	13 05 40.2	−25 41 06	19.2	0.3–1 Gyr	16, 17, 21, 22
TVLM 868−110639[d]	15 10 17.2	−02 41 07	25.4	…	16, 17, 20

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

REFERENCES.—(1) Martín et al. 2001; (2) Pascucci et al. 2003; (3) Béjar et al. 2001; (4) Mokler & Stelzer 2002; (5) Luhman 1999; (6) Scholz et al. 1999; (7) Ardila et al. 2000; (8) Preibisch et al. 1998; (9) de Zeeuw et al. 1999; (10) Festin 1998a, 1998b; (11) Mermilliod et al. 1997; (12) Stauffer, Schultz, & Kirkpatrick 1998; (13) Leggett et al. 1999; (14) Nakajima et al. 1995; (15) Oppenheimer et al. 1995; (16) Dahn et al. 2002; (17) Kirkpatrick et al. 2000; (18) Freed, Close, & Siegler 2003; (19) Gliese & Jahreiss 1991; (20) Leggett, Allard, & Hauschildt 1998; (21) Martín, Brandner, & Basri 1999; (22) Ruiz, Leggett, & Allard 1997.

[a] Lower limit for the objects for which no individual age estimate is available. Comparison with evolutionary tracks suggests ages of the order of 100 Myr and higher (see Dahn et al. 2002).

[b] Binary BD.

[c] BD companion.

[d] Objects at the substellar boundary.

All the targets with their ages and distances are compiled in Table 1.

The observations were carried out at the JCMT on Mauna Kea, Hawai'i, and at the IRAM 30 m telescope, Pico Veleta, Spain. At the JCMT, we used the 37-channel array camera SCUBA (Holland et al. 1999) at a wavelength of 850 μm. At the IRAM 30 m telescope, we performed the observations at 1.3 mm with the 37-channel array camera MAMBO (Kreysa et al. 1998). These wavelengths are a good trade-off between the expected flux and the opacity of the atmosphere.

The observations were performed between 2002 March and 2003 January. The chosen observing mode is point-source photometry using the central bolometer of SCUBA and MAMBO, respectively. The background (telluric and astronomical) subtraction is achieved by chopping with the secondary mirror and nodding the telescope. Its level has been estimated from the inner ring consisting of six bolometer pixels.

The measured flux densities and derived upper limits are listed in Table 2. For many sources, we can only derive upper limits since the signal-to-noise ratio is less than 3. The upper limits are given as 3 σ values, where σ is the standard deviation of the statistical error.

3. RESULTS

We detected millimeter continuum emission associated with two BDs. Both, CFHT-BD-Tau 4 and IC 348 613, were detected at two wavelengths, i.e., with the JCMT at 850 μm and with the IRAM 30 m telescope at 1.3 mm. These detections can be used to estimate the amount of circumstellar matter around these BDs for the first time.

Carpenter (2002), however, using the OVRO interferometer to map IC 348, did not detect IC 348 613. The reason is that he mapped at a wavelength of 3 mm. If we extrapolate the measured flux densities to a wavelength of 3 mm, the flux density falls just below the detection limit of the OVRO map.

3.1. *Dust Masses*

The measured flux density F_ν at submillimeter/millimeter wavelengths is certainly optically thin thermal emission by cold dust heated by the BD. The dust mass M can be derived using the formula

$$M = \frac{F_\nu D^2}{B_\nu(T, \lambda)\kappa_\nu(\lambda)},$$

where F_ν stands for the flux density, B_ν for the Planck function, T for the dust temperature, and κ_ν for the mass absorption coefficient. The quantity D is the distance to the object. Likewise, upper limits for the flux density are translated into upper limits for the amount of circumstellar matter.

Among the above quantities, the distances are well estab-

TABLE 2
Observational Results

BDs	Flux at 850 μm (mJy)	Flux at 1.3 mm (mJy)	Dust Mass (M_E)
BDs in Taurus:			
CFHT-BD-Tau 1	…	<2.73	<4.8
CFHT-BD-Tau 2	<5.81	…	<4.1
CFHT-BD-Tau 4	10.8 ± 1.8	2.1 ± 0.6	1.4–7.6
BD in σ Ori cluster:			
S Ori 03		<2.97	<32
BD in IC 348:			
IC 348 613	7.6 ± 2.4	2.8 ± 0.8	5.4–18
BDs in Upper Scorpius:			
U Sco 100	<4.09	…	<3.1
U Sco 104	<5.27	…	<3.8
U Sco 112	<6.11	…	<4.4
U Sco 128	<8.35	…	<6.3
BDs in the Pleiades:			
NPL 36	<6.04	…	<6.7
NPL 37	<4.18	…	<4.6
NPL 38	<4.04	…	<4.4
NPL 30 (Teide 1)	<4.39	…	<4.9
Field BDs:			
Gl 229B	<9.41	…	<0.03
2MASSI J0746425+200032	<3.76	…	<0.05
2MASSI J0825196+211552	<5.16	…	<0.07
LHS 2397a	<4.79	…	<0.08
Kelu 1	<2.15	…	<0.06
TVLM 868−110639	<6.73	…	<0.36

lished from trigonometric parallaxes in the case of most of the field BDs. For the young BDs, we used the known distances to the clusters/star-forming regions. However, the dust properties κ_ν and the dust temperature T need a more thorough discussion.

The targeted BDs have a large spread in age, and we would expect different evolutionary stages of the disk material, if present at all. Therefore, we will apply two different sets of dust parameters (see, e.g., Henning, Michel, & Stognienko 1995). The “young” dust parameters will be applied to BDs with ages up to 10 Myr. The “debris” dust parameters will be used for the other objects, which are all older than 100 Myr. We assume a constant dust temperature as an approximation to the temperature distribution of the circumstellar dust. In the following paragraphs, we discuss the two sets of dust parameters.

Young dust.—For dust around young BDs, we choose, for the sake of comparison, a mass absorption coefficient of $\kappa_\nu = 2$ cm^2 g^{-1} at 1.3 mm. The same value of κ_ν and a gas-to-dust ratio of 100 were applied by Beckwith et al. (1990) to derive disk masses for T Tauri disks. For the measurements at 850 μm, we assume a wavelength dependence of $\kappa_\nu \propto \lambda^{-\beta}$ with $\beta = 1$, also in accordance with Beckwith et al. (1990). This leads to $\kappa_\nu = 3$ cm^2 g^{-1} at 850 μm.

The plausible range of dust temperatures is relatively small. We assume an average temperature of 10–20 K for the dust. This is the range of the mass-averaged dust temperature in the models for the disk around CFHT-BD-Tau 4 discussed by Pascucci et al. (2003).

Debris dust.—The BDs in the Pleiades and the field objects are presumably older than 100 Myr. At this age, one can no longer assume a T Tauri–like disk with its dust properties. If there is a disk left, it will resemble debris disks like the β Pictoris disk. To allow comparisons with submillimeter observations of debris disks, we adopted the mass absorption coefficient used by Dent et al. (2000), i.e., $\kappa_\nu = 0.4$–1.7 cm^2 g^{-1} at 850 μm. The gas-to-dust mass ratio in debris disks is controversial (Thi et al. 2001; Lecavelier des Etangs et al. 2001). Therefore, we will only give the dust masses in these cases.

Since debris disks are optically thin, the circumstellar dust grains around the old BDs have at least the temperature of interstellar grains, i.e., 20–30 K depending on the composition and the actual interstellar radiation field at the position of the BDs. The heating of the dust by the old BD is negligible; thus, we assume a temperature between 20 and 30 K.

Applying the above-discussed dust properties to the millimeter continuum measurements, we obtain the dust masses compiled in Table 2. The ranges result from the uncertainties in the mass absorption coefficient and the temperature. Furthermore, the millimeter emission has been measured at two wavelengths for the detections. The mass estimates derived from the two measurements differ slightly. For the detections, the masses in Table 2 correspond to the minimum and maximum mass estimates. In the case of nondetections, the mass limits are derived from the 3 σ flux limits using the dust parameters yielding the highest masses.

The mass of circumstellar dust for CFHT-BD-Tau 4 is between $1.4M_E$ and $7.6M_E$, and for IC 348 613, the mass is between $5.4M_E$ and $18M_E$. The dust is certainly distributed in the form of disks, as detailed analyses of CFHT-BD-Tau 4 by Pascucci et al. (2003) show. The disk masses for the two BDs are $(0.4$–$2.4)M_J$ (Jupiter mass) and $(1.7$–$5.7)M_J$, if we extrapolate the dust masses to disk masses by assuming a gas-to-dust ratio of 100. The upper limits on the circumstellar dust mass around the other young BDs are around a few Earth masses.

The dust mass constraints for the nearby field BDs are even more stringent, reaching upper limits of some Moon masses. Thus, even around the low-luminosity BDs, circumstellar disks cannot be long-lived. Debris disks around the old BDs, which may be associated with planetary systems, cannot be ruled out since we were not sensitive down to fractions of Moon masses of dust that is the order of the dust mass around the low-mass main-sequence star ϵ Eridani (Dent et al. 2000).

3.2. *Disks around Young BDs*

One important question about BDs and their disks is the mass ratio of the central objects and the circumstellar material. The BDs' masses themselves [CFHT-BD-Tau 4: $M_* = (30–75)M_J$,[1] Martín et al. 2001; IC 348 613: $M_* = (20–40)M_J$, Preibisch & Zinnecker 2001], as well as the disk masses, are uncertain. Therefore, we do not attempt to estimate their ratio here. Still, we note that the observations are consistent with a disk/BD mass ratio of a few percent as it is found for most of the T Tauri stars.

The detection of some Jupiter masses of matter around BDs is especially interesting for extrasolar planet searches. Guenther & Wuchterl (2003) mention that planets may form around a BD if a disk of enough mass is present. Their radial velocity survey targets very low mass stars and BDs because these targets are relatively inactive. Furthermore, young planets around BDs would be the easiest to detect by direct imaging because the contrast between the BD and its planet would be much more favorable than for a planet around a higher mass star.

4. SUMMARY

The observing campaign targeting BDs of several populations resulted in detections of millimeter emission associated with two young BDs. The mass estimates for the young BD disks are $(0.4–2.4)M_J$ and $(1.7–5.7)M_J$ for CFHT-BD-Tau 4 and IC 348 613, respectively. For the other targets, stringent upper limits on the amount of circumstellar matter were derived from the measured upper limits on the millimeter continuum flux densities. To estimate the dust masses, two sets of dust properties had to be applied: young dust properties to BDs younger than 10 Myr and debris dust properties to BDs older than 100 Myr.

The detection of a few Jupiter masses of circumstellar matter around young BDs is an important result. To ensure this mass estimate, the dust properties have to be constrained further. However, a refinement of the dust properties will hardly change the fact that there are substantial amounts of circumstellar material around the two BDs CFHT-BD-Tau 4 and IC 348 613. Thus, the detections show that BDs may be places of planet formation. This fact opens a new set of targets for extrasolar planet searches, especially for direct imaging, because of the low contrast between the central object and a prospective planet.

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[1] Martín et al. (2001) derive a mass of 0.03 $M_\odot$ for CFHT-BD-Tau 2 and 3 with spectral types M8 and M9, respectively. CFHT-BD-Tau 4 has the spectral type M7 and is more luminous than the 1 Myr isochrone. This suggests that CFHT-BD-Tau 4 is more massive, possibly close to the stellar/substellar boundary.

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