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FIRST EVIDENCE FOR DUSTY DISKS AROUND HERBIG BE STARS

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ABSTRACT

We have carried out a high-sensitivity search for circumstellar disks around Herbig Be stars in the continuum at 1.4mm and 2.7mm using the IRAM interferometer at the Plateau de Bure (PdBI) . In this letter, we report data on three well studied B0 stars, MWC 1080, MWC 137 and R Mon. The two latter have also been observed in the continuum at 0.7 cm and 1.3 cm using the NRAO Very Large Array (VLA) . We report the detection of circumstellar disks around MWC 1080 and R Mon with masses of $M_d \sim 0.003$ and 0.01 $M_\odot$, respectively, while for MWC 137 we estimate a disk mass upper limit of 0.007 $M_\odot$. Our results show that the ratio M_d/M_* is at least an order of magnitude lower in Herbig Be stars than in Herbig Ae and T Tauri stars.

Subject headings: Radio continuum: stars – Circumstellar matter – Stars: individual (MWC 1080, MWC 137, R Mon) – stars:pre-main sequence

1. INTRODUCTION

The existence of accretion disks around massive stars ($M > 5\ M_\odot$) remains a matter of debate. There is increasing evidence for the existence of flattened structures (disks) around high-mass protostars. However there is no clear evidence of disks in later phases, namely in Herbig Be (HBe) stars. Natta et al. (2000) compiled the interferometric observations in mm continuum around HBe stars and found that the occurrence of disks in HBe is $\sim$ 0. This contrasts with the case of the lower mass HAe stars ($2M_\odot \leq M_* \leq 5\ M_\odot$) in which the occurrence of circumstellar disks is similar to that in T Tauri stars. They propose that the lack of disks around HBe stars is due to the rapid evolution of these objects, which disperse the surrounding dust and gas in about 10^6 yrs (Fuente et al. 2002). However, this lack of detection can be a sensitivity effect. HBe stars are usually further away than HAe stars, and higher sensitivity interferometric observations are required to detect circumstellar disks around these objects. In this Letter, we present the first results of a high-sensitivity search for circumstellar disks around three B0 stars, MWC 1080, MWC 137 and R Mon, which are the best studied of the five Herbig B0 stars in the northern sky listed by Thé et al. (1994).

2. OBSERVATIONS

Interferometric observations in the continuum at 1.4mm and 2.7mm have been carried out towards the Herbig Be stars MWC 1080, MWC 137 and R Mon, using the IRAM[5] array at Plateau de Bure, France, in the CD set of configurations. MWC 137 and R Mon, were also observed with the NRAO[6] Very Large Array (VLA) at 0.7 cm and 1.3 cm in its D configuration. Flux calibration is accurate within 10% at 2.7mm and 20% at 1.4mm in the PdBI images and within 20% in the VLA images. No correction for primary beam attenuation has been applied. PdBI and VLA images are shown in Fig 1. Flux densities at the star positions are shown in Table 1.

3. MWC 1080

Although, we have not observed MWC 1080 at cm wavelengths. some information about the cm emission can be found in the literature. Curiel et al. (1989), from $10''$ resolution observations at 6cm, detected a weak extended component which includes the star and the reflection nebula. Skinner et al. (1993) with higher angular resolution ($\sim 1''$) tentatively detected at 3.6cm a compact source at the star position. Recently, Girart et al. (2002) detected three 6cm sources using the VLA with an angular resolution of $\sim 5''$. One of these sources is coincident with the star position. They did not detect a counterpart of this emission at 2.0cm with an upper limit of ≤ 0.32 mJy.

Intense emission is detected in the millimeter continuum images observed with the PdBI (see Fig 1ab). Interferometric observations at 2.7mm in MWC 1080 were previously reported by Di Francesco et al. (1997) with a non-detection. Our image improves by a factor of 10 the sensitivity and by a factor of 2 the angular resolution of their data. The millimeter continuum emission in MWC 1080 is extended. Two intense components connected by a bridge of weak emission are observed in the 2.7mm image. These components are much closer to the star than the VLA 6cm sources detected by Girart et al. (2002). We will refer to these components as "NW" and "SE". The better angular resolution of the 1.4mm image resolve the "NW" and "SE" clumps in several components, "NW1", "SE1", "SE2" and "*Star*". The total flux in the 1.4mm image is $\sim$ 24 mJy. In our single-dish data we measured a 1.4mm flux of 73.8 mJy at the star position with an angular resolution of $\sim 10.''5$ (Fuente et al. 1998). Thus the interferometer has resolved the 1.4mm emission and missed $\sim$ 70% of the flux. The "Star" com-

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ponent is coincident with the optical star position and remains unresolved in the 1.4mm image. This implies that its size is < 2" which corresponds to a spatial extent of <2000 UA at the distance of MWC 1080 (d=1000pc). This size is compatible with the emission arising in a circumstellar disk.

4. MWC 137

MWC 137 is associated with the one-arcminute size HII region S266 (Fich 1993). Observations of this region at 3.6cm were reported by Skinner et al. (1993). Our 1.3cm image of MWC 137 consists of a compact source coincident with the HBe star surrounded by a thin shell with a radius of 30"-40" from the point source. Weak emission is found towards the thin shell and the point source. In the 0.7cm image, the compact source appear more intense while the emission of the thin shell becomes fainter. Since our aim is the detection of a circumstellar disk, we are only interested in the compact component (see Table 1).

The continuum millimeter images show intense emission centered at the star position. The total flux in the 1.4mm image is $\sim$ 10 mJy, i.e. $\sim$ 30% of the flux measured in the single-dish observations (Fuente et al. 1998). From our 1.4mm image we derive a source size of 1.8$''$ $\times$ 0.8$''$, which corresponds to $\approx$ 2300 AU $\times$ 1000 AU assuming a distance of 1300 pc and a position angle of 75$\pm$15deg. Note that the accuracy of the position angle estimate is heavily limited by the S/N ratio of the data.

5. R MON

R Mon was observed at 6cm, 3.6cm and 2cm using the VLA by Skinner et al. (1993). They detected continuum emission at a position slightly shifted from the optical one. A compact source is detected in R Mon at 1.3cm and 0.7cm. The position of this source is offset (0.74",-0.45") from the optical position but coincident with the radio source. A jet-like feature is observed in the 1.3cm image which is surely driven by the radio source. This jet was already detected by Brugel et al. (1984) in optical lines. Since the uncertainty of the optical position is not known, the identification of the radio source with R Mon is uncertain.

We have detected continuum emission towards the star in the 2.7mm image with a peak emission of 4.1 mJy/beam. The total integrated flux is 6.4 mJy revealing that the emission is extended. Deconvolving the 2.7mm image with the beam, we estimate an emission size of 3"–4", which corresponds to $\approx$ 3000 AU at the distance of 800 pc. Natta et al. (2000) reported a total 2.7mm flux of 13.0$\pm$1.3 mJy towards R Mon based on unpublished data by Mannings (1998). This flux exceeds by a factor of 2 our present result. This reinforces our conclusion that the emission is extended. Then, the different beams and calibration uncertainity can account for this discrepancy.The 2.7mm continuum emission is elongated in the direction perpendicular to the bipolar nebula axis and the centroid of the emission lies to the northeast of the position of the radio-source. The shape and position of the 2.7mm emission suggest that the 2.7mm emission is tracing a different emission component from that traced by the emission at cm wavelengths, and argues in favor of the existence of a flattened structure (disk) around the star.

6. SPECTRAL ENERGY DISTRIBUTIONS (SEDS)

The SEDs in the cm-mm range of MWC 1080, MWC 137 and R Mon are shown in Fig. 2. In order to avoid the contribution of the envelopes of these sources to the continuum emission, only interferometric measurements have been included in these SEDs. Even though, some problems still remain. The emission at cm wavelengths in MWC 1080 is extended. The negative index derived by comparing the flux at 6cm and 3.6cm is very likely due to the larger beam of the 6cm flux (5.5$''\times$5.03$''$) compared with that of the 3.6cm one (1.24$''\times$0.83$''$). The disk emission should be unresolved at the distance of our source. Therefore, we are not interested in the extended component and consider the 6cm flux as an upper limit. Unfortunately, the free-free emission arising in the stellar wind is also expected to be unresolved with our beam and could make an important contribution to the continuum flux even at millimeter wavelengths. In order to derive the disk mass in MWC 1080, we have assumed that the 3.6cm flux is due to free-free wind emission and subtracted it from the observed mm fluxes. These corrected values are then interpreted as optically thin disk emission, according to the expression $F_\lambda = d^{-2} M_d \kappa_\lambda B_\lambda(T_d)$ with $\kappa = 0.01(\lambda(mm)/1.3)^{-\beta} cm^{-2} g^{-1}$. We have assumed a constant value of T_d = 215 K following the recommendation of Natta et al. (2000) for B0 stars. With these assumptions, we obtain from the 1.4mm flux a disk mass of 0.003 $M_\odot$. Since we have only an upper limit to the 2.7mm flux, the value of β cannot be determined. We have compared the disk mass derived with this simplified expression to those of more elaborated models (see Dullemond et al. 2002), varying the disk outer radius and the surface density profile over a large range of possible values, and confirmed the conclusion of Natta et al. (2000) that the values of M_d derived in this way are accurate within a factor 2 – 3. We have also considered the possibility that the 3.6cm emission arise in an optically thin HII region instead of free-free emission. With only two points in the SED, we cannot discern between these two possibilities. In this case, we obtain a slightly larger value of the disk mass of, $M_d \sim 0.004\ M_\odot$. Therefore we estimate that the mass of the disk around MWC 1080 is 0.003$\pm$0.001 $M_\odot$.

The complete SED of MWC 137 can be fitted with a single component with spectral index $\alpha = +0.76\pm0.01$. This spectral index is consistent with that expected in the free-free emission arising in the stellar wind. Although a value of α =+0.6 is expected for a ionized isotropic wind, small deviations of this value can be explained by a different geometry or a partially ionized wind. However, we cannot discard the existence of a very low-mass disk. In order to estimate an upper limit to the disk mass, we have extrapolated the 3.6cm flux to millimeter wavelengths with an spectral index of +0.6. Then, we have estimated the disk mass from the excess flux at 1.4mm. With the same values of κ and T_d than in the case of MWC 1080, we obtained an upper limit to the disk mass of 0.007 $M_\odot$.

The SED of R Mon is the most complete one. We have been able to fit all the centimeter data using a spectral index, $\alpha_{cm} \approx 0.64$, which is characteristic of a spherical stellar wind. In order to estimate the mass of the circumstellar disk, we have extrapolated the free-free emission to millimeter wavelengths and fit the millimeter part of the SED with a simple disk model. As in the case of MWC 1080, we have assumed an unresolved disk at a constant temperature, $T_d = 215$ K and adjusted the value of M_d and β. Only values of $\beta = 0.25 - 0.5$ fit our observational points. A value of β larger than 0.5 would produce an excess of flux at 1.4mm. This low value of β could be interpretred as an optically thick compact disk, or an optically thin disk with large grains. The first possibility would imply millimiter fluxes larger than those measured. A small disk of R = 100 AU should have a mass of 0.35 $M_\odot$ in order to have $\tau_{1.4mm}$~1. But in this case, the 1.4mm flux would be at least an order of magnitude larger than our upper limit. The situation would be worse for a larger disk. The second possibility seems more plausible. Similarly low values of β have been found in Herbig Ae and T Tauri disks and reveal highly processed dust (Beckwith & Sargent 1991; Testi et al. 2003). With the fiducial value of the dust emissivity, we derive a disk mass of 0.01 $M_\odot$. Note, however, that, if the low value of β is interpreted as evidence of grain growth, one needs to reduce the fiducial 2.7mm dust emissivity by a factor of about 4 (Testi et al. 2003), and to increase the estimated disk mass by a similar amount.

7. DISK DETECTIONS IN HBE STARS

Our results prove the existence of circumstellar dust around MWC 1080 and R Mon. However, it is very difficult to interpret it beyond doubt as evidence of a circumstellar disk. In general, a compact and small 1.4mm source ($< 1'' - 2''$) at the star position is considered as a disk detection. This criterium seems sufficient in TTS located at distances of $\sim$ 150 pc, in which an angular resolution of $1''$ corresponds to a linear scale of 100 - 200 AU , typical size of circumstellar disks. Since HBe stars are usually located at distances larger than 1 Kpc, even the higher angular resolution provided by interferometers, $\sim 1''$, corresponds to sizes of a few thousands of AU, and it is not possible to distinguish between "bonafide" circumstellar disks and a flattened structure of a few 1000 AU.

Another difficulty comes from the fact that many HBe stars are likely associated to lower mass companions that will not be resolved in our beam. MWC 1080 is a close binary with a separation of 0.7 $''$ (Leinert et al. 1997). Mid-infrared observations by Polomski et al. (2002) using the Keck II telescope resolve the binary and found that warm material ($\sim$ 350 K), with a $3 - 10$ μm spectral index consistent with the existence of a circumstellar disk, is surrounding MWC 1080 A. A cooler dust component is associated with MWC 1080 B. We have detected an unresolved mm continuum source in MWC 1080. We consider that this source is a good candidate for disk detection around a HBe star. However, since the angular resolution of our observations is not sufficient to resolve the two binary components, we cannot exclude the possibility that the emission is associated with the younger companion.

R Mon is also a close binary with a separation of 0.69". Its companion is a very young TTS. Close et al. (1997) found an extinction of Av = 13.1 mag towards the star which they interpreted as due to an optically thick disk of R = 100 AU. Our 2.7mm image reveals the existence of a compact source of $\approx$ 3000 AU $\times$ 2300 AU. This size is larger than that expected for a circumstellar disk and suggests the existence of a flattened envelope surrounding the disk. Our value of the disk mass may be overestimated due to the contribution of the flattened envelope. However, the analysis of the mm spectral index shows that the grains responsible of the emission are heavily processed, so that most of the emission is very likely arising in a circumstellar disk. If this is true, it is unlikely that the disk could be associated to the TTS companion, since in this case one should use in deriving the disk mass a value of $T_d \sim 15$ K (Natta et al. 2000) and the estimated mass would increase to values in the range 0.2–0.5 $M_\odot$, too large for a TTS disk.

We have completed the compilation of (interferometric) disk observations of HAeBe stars carried out by Natta et al. (2000) with the observations in MWC 1080, MWC 137 and R Mon reported in this paper, and the observations in HD 200775 and LkHα 234 reported by Fuente et al. (2001). In Fig. 3, we plot the disk masses as a function of the spectral type of the star and the stellar age. We have plotted MWC 1080 and R Mon as disk detections; however, as discussed in the previous section, it is possible that the "disk" emission is either overestimated or not associated to the Herbig Be star itself, but to unresolved companions, thus reinforcing our conclusions. In any case, disk masses in HBe stars are at least an order of magnitude lower than in HAe stars. Plotting M_d/M_* as a function of the spectral type, one finds that while the value of M_d/M_* is roughly constant and equal to 0.04 for stars with spectral type A0-M7, $M_d/M_* <$ 0.001 in HBe stars. The same effect remains when one plots the disk mass against the stellar age. The values of disk masses in HBe stars are systematically lower than in HAe stars for stars with ages between 10^5 and 10^7 yrs. This lack of massive disks in HBe stars even for stars as young as 10^5 years put several constraints to the possibility of forming planetary systems around massive stars. In a time-scale of $< 10^6$ years the disk mass around a HBe star is similar to or even lower than the total mass of the planets in the solar system ($\sim$ 0.0013 $M_\odot$). Thus planet formation should occur very fast, for planetary systems to exist at all around massive stars.

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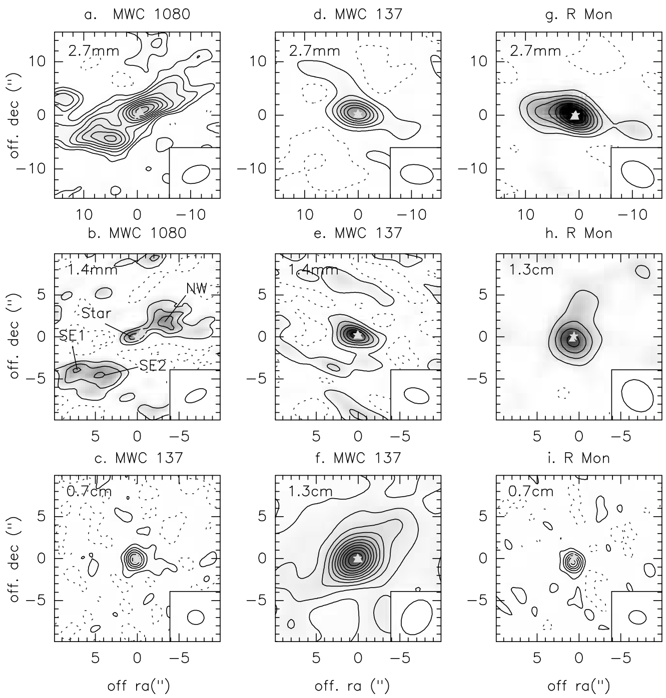
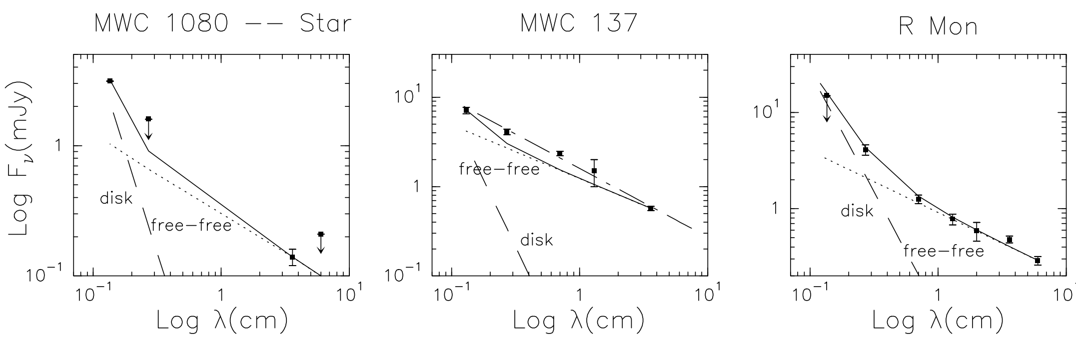
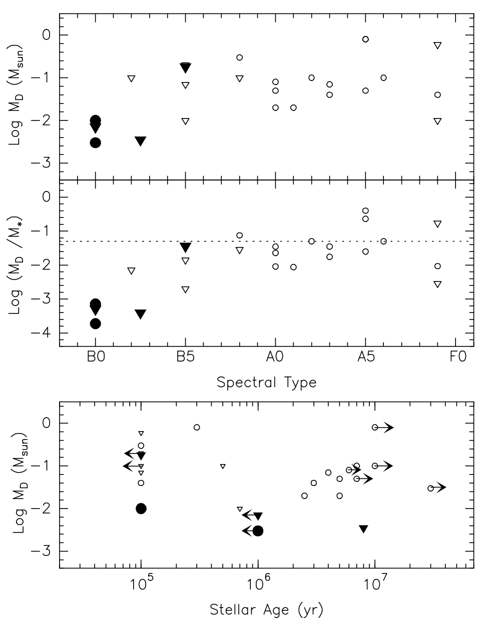
Table 1
Observed fluxes.

Object	$S_{1.3cm}$ (mJy/beam)	$S_{0.7cm}$ (mJy/beam)	$S_{2.7mm}$ (mJy/beam)	$S_{1.4mm}$ (mJy/beam)
MWC 1080	...	...	< 1.7	3.1 (0.2)
MWC 137	1.5(0.5)[1]	2.35(0.13)	4.1(0.2)	7.1(0.6)
R Mon	0.78(0.10)	1.26(0.13)	4.1(0.5)	< 15

[1] Subtracting the emission of the extended component


a. MWC 1080
2.7mm
d. MWC 137
2.7mm
g. R Mon
2.7mm
b. MWC 1080
1.4mm
NW
Star
SE1
SE2
e. MWC 137
1.4mm
h. R Mon
1.3cm
c. MWC 137
0.7cm
f. MWC 137
1.3cm
i. R Mon
0.7cm
off. dec (")
off ra(")
off. ra (")
off ra(")


MWC 1080 -- Star
MWC 137
R Mon
Log F_ν(mJy)
Log λ(cm)
disk
free-free



Log M_D (M_{sun})
Log (M_D /M_*)
B0
B5
A0
A5
F0
Spectral Type
Log M_D (M_{sun})
10^5
10^6
10^7
Stellar Age (yr)

FIG. 1.— Continuum images obtained with the PdB and VLA arrays. The star marks the optical position [MWC 1080 : 23:17:25.574 60:50:43.34; MWC 137: 06:18:45.504 +15:16:52.4; R Mon: 06:39:09.94 +08:44:10.0] and the filled triangle the position of the radio source (Skinner et al. 1993). Contour levels are: **a.** -2.0 to -0.2 mJy/beam and 0.2 to 4.0 mJy/beam by 0.2 mJy/beam; **b.** -1.6, -0.7, 0.7 to 3.4 mJy/beam by 0.9 mJy/beam; **c.** -0.2 mJy/beam, 0.2 to 2.2 mJy/beam by 0.4 mJy/beam; **d.** -0.3 mJy/beam, 0.3 to 3.6 mJy/beam by 0.6 mJy/beam; **e.** -1.8 mJy/beam, -0.6 mJy/beam 0.6 to 6.6 mJy/beam by 1.2 mJy/beam; **f.** -0.2 mJy/beam, 0.2 to 2.4 mJy/beam by 0.2 mJy/beam; **g.** -0.5 mJy/beam, 0.5 to 4.0 mJy/beam by 0.5 mJy/beam; **h.** -0.2 mJy/beam, 0.2 to 0.8 mJy/beam by 0.2 mJy/beam; **i.** -0.2 mJy/beam 0.2 to 1.4 mJy/beam by 0.2 mJy/beam.

FIG. 2.— Spectral energy distributions (SEDs) at cm and mm wavelengths of MWC 1080, MWC 137 and R Mon. The fluxes at cm wavelengths have been taken from Skinner et al. (1993) and Girart et al. (2002), and at mm wavelengths are from this paper. The short-dash lines are model predictions for the free-free emission component. The long-dash lines are model predictions for circumstellar disks of 0.003 $M_\odot$ and β=1 (MWC 1080), 0.007 $M_\odot$ and β=1 (MWC 137), and 0.01 $M_\odot$ and β=0.5 (R Mon). The solid line is the sum of both components. The short-long straight line in central panel is the predicted fluxes for the emission arising in a stellar wind with α= +0.76 in MWC 137.

FIG. 3.— Plot of the M_d and M_d/M_* versus the spectral type of the star (**top panels**) and M_d versus the stellar age (**bottom panel**) for a wide sample of HAEBE stars. Data have been taken from the compilation by Natta et al. (2000) (empty symbols) and the results reported by Fuente et al. (2001) and this paper (filled symbols).Dots mean detections while triangles mean upper limits. Note that disk masses in HBe stars are at least an order of magnitude lower than in HAe stars.