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GREAT: early science results

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Letter to the Editor

GREAT [C II] and CO observations of the BD+40°4124 region

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ABSTRACT

The BD+40°4124 region was observed with high angular and spectral resolution with the German heterodyne instrument GREAT in CO $J = 13 \rightarrow 12$ and [C II] on SOFIA. These observations show that the [C II] emission is very strong in the reflection nebula surrounding the young Herbig Ae/Be star BD+40°4124. A strip map over the nebula shows that the [C II] emission approximately coincides with the optical nebulosity. The strongest [C II] emission is centered on the B2 star and a deep spectrum shows that it has faint wings, which suggests that the ionized gas is expanding. We also see faint CO $J = 13 \rightarrow 12$ at the position of BD+40°4124, which suggests that the star may still be surrounded by an accretion disk. We also detected [C II] emission and strong CO $J = 13 \rightarrow 12$ toward V 1318 Cyg. Here the [C I] emission is fainter than in BD+40°4124 and appears to come from the outflow, since it shows red and blue wings with very little emission at the systemic velocity, where the CO emission is quite strong. It therefore appears that in the broad ISO beam the [C II] emission was dominated by the reflection nebula surrounding BD+40°4124, while the high J CO lines originated from the adjacent younger and more deeply embedded binary system V 1318 Cyg.

Key words. circumstellar matter – ISM: molecules – stars: pre-main sequence – photon-dominated region (PDR) – stars: variables: T Tauri, Herbig Ae/Be

1. Introduction

The BD+40°4124, at a distance of 980 pc (Shevchenko et al. 1991), forms a a small pre-main-sequence cluster (Herbig 1960; Hillenbrand et al. 1995). Herbig (1960) included BD+40°4124 in his original list of Herbig Ae/Be (HAEBE) stars and noted that it had three companions: LkHα 224 (V 1686 Cyg), LkHα 225 (V 1318 Cyg), and LkHα 226 within 35″ of BD+40°4124. Both BD+40°4124 and V 1686 Cyg are HAEBE stars with spectral types of B2 Ve and A7 Ve, respectively (van den Ancker et al. 1998; van den Ancker et al. 2000). Hillenbrand et al. (1995), however, classified V 1686 Cyg as B5 Ve. V 1318 Cyg is a heavily obscured binary system with a separation of ~5″ (Aspin et al. 1994). The southern member of this binary, V 1318 Cyg S, is more deeply embedded with a visual extinction of 10 mag or more. Several studies indicate that V 1318 Cyg may have a hidden companion about 1″ to the NE that powers the outflow and the H_2O maser (Davies et al. 2001; Marvel 2005). The spectral type of V 1318 Cyg is very uncertain, but based on analysis of the spectral energy distribution, both Aspin et al. (1994) and van den Ancker et al. (2000) argued that at least one of the stars must be an intermediate mass star. Hillenbrand et al. (1995) gave spectral classifications of mid-A to Fe for both components. A K-band image of the BD+40°4124 field is shown in Fig. 1.

BD+40°4124 illuminates a bright reflection nebula with a radius of ~30″ (Herbig 1960; Loren 1977; Hillenbrand et al. 1995), while V 1318 Cyg excites an H_2O maser and drives a bipolar molecular outflow (Palla et al. 1995). The BD+40°4124 region was studied in the infrared by several groups using both the ISO SWS and LWS spectrometers (van den Ancker et al. 2000; Creech-Eakman et al. 2002; Lorenzetti et al. 2002).

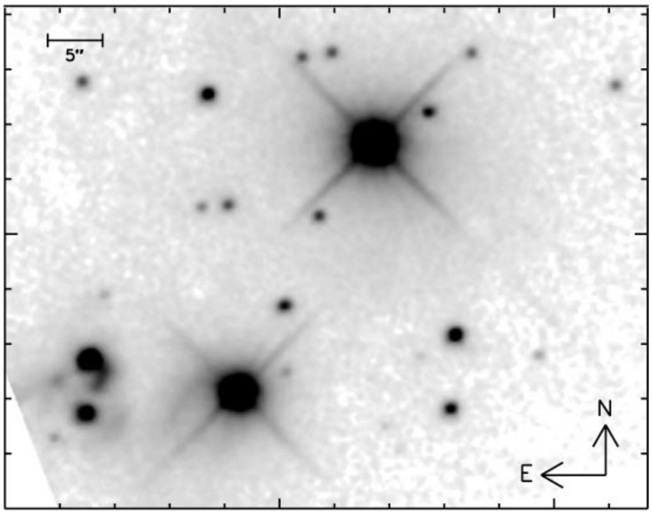

Fig. 1. A K-band image of the BD+40°4124 field from Davies et al. (2001). BD+40°4124 is the bright star in the northern part of the image, while the second bright star 26″ to the south east is V 1686 Cyg. V 1318 Cyg is the double star system at the south eastern edge of the image. The southern star is the active one, showing strong H_2 emission and powers a massive bipolar molecular outflow.

ISO LWS spectra were obtained toward BD+40°4124, V 1686 Cyg, and V 1318 Cyg, even though they are all covered with one pointing, since the beam width for LWS is ∼80″. Creech-Eakman et al. (2002) and Lorenzetti et al. (2002) attributed all the [C ii] and high transition CO (J = 14 → 13 to J = 16 → 15) emission to BD+40°4124, while van den Ancker et al. (2000) assigned about the same amount of [C ii] emission to BD+40°4124 and V 1318 Cyg, and no emission at all to V 1686 Cyg.

In this Letter we revisit the BD+40°4124 region with the GREAT[1] heterodyne instrument on SOFIA to see where the [C ii] and high J CO emission really comes from. Is it dominated by the bright reflection nebulosity illuminated by BD+40°4124 or does the emission come from the younger, embedded star V 1318 Cyg? Given the low spatial resolution of the ISO data, it is clear that higher resolution data are needed to determine where the [C ii] and CO emission comes from and which physical mechanisms generate this emission.

2. Observations

BD+40°4124 and V 1318 Cyg were observed with GREAT on SOFIA on April 6, 2011 on a 53 min leg at an altitude of 43 000 ft. GREAT is a modular heterodyne instrument, with two channels that are both used simultaneously. For a more complete description of the instrument, see Heyminck et al. (2012). For this flight, which was the first science flight with GREAT, the configuration was set to the low-frequency channel 1b ($L1_b$), which covers the frequency range 1.42–1.52 THz, and the low-frequency channel 2 (L2), covering 1.82–1.92 THz. The $L1_b$ channel was tuned to CO J = 13 → 12 (1496.923 GHz) in the lower sideband and the L2 channel was centered on the [C ii] $^2P_{3/2}$ → $^2P_{1/2}$ (1900.5369 GHz) in the upper sideband. The half power beam width (HPBW) is ∼21″ at 1.5 THz and 16″ at 1.9 THz. As backend we used the fast Fourier transform spectrometers (AFFTS), which have a bandwidth of 1.5 GHz and 8192 channels and provide a frequency resolution of 0.212 MHz. The measured system temperatures were ∼4500 K for [C ii] and 3000 K for CO = 13 → 12. All observations were made in dual beam switch mode using a 150″ chop amplitude in equatorial coordinates at a position angle of 135°. We took "long" integration spectra toward both BD+40°4124 and V1318 Cyg with total integration times of 2.5 and 3.7 min, respectively. We also obtained a strip map over BD+40 in RA with 15″ spacing going from −15″, 0″ to +45″, 0″ to explore how extended the [C ii] emission was. The integration time for these spectra was 0.6 min/position. The spectra were analyzed in CLASS, where we coadded individual spectra and removed a linear baseline. All spectra are calibrated in T_A^* and corrected for a forward scattering efficiency of 0.95.

3. Results

3.1. BD+40°4124

The [C ii] emission is quite strong toward BD+40°4124 with an antenna temperature of T_A ∼ 13.5 K (Fig. 2, Table 1). In Fig. 3 we show the positions of the strip map that we obtained of BD+40°4124 marked as crosses on the 850 μm SCUBA image from Sandell et al. (2011). The strip map (Fig. 4) shows that the [C ii] emission peaks within errors on the star and slowly decreases to the east. There does not appear to be any interaction between the [C ii] emission and the dense molecular ridge (see Fig. 3), which extends from V 1318 Cyg to the north past BD+40°4124 (Sandell et al. 2011; Looney et al. 2006). There are no changes in the [C ii] brightness as it crosses over the ridge, nor

[1] GREAT is a development by the MPI für Radioastronomie and the KOSMA/Universität zu Köln, in cooperation with the MPI für Sonnensystemforschung and the DLR Institut für Planetenforschung.

Table 1. Gaussian fits to long integration spectra.

Source	Line	$\int T_A^* dV$ [K km s^{-1}]	T_A^* [K]	ΔV [km s^{-1}]	V_{LSR} [km s^{-1}]
BD+40°41247	[C ii]	21.7 ± 1.7	9.9	2.1 ± 0.1	7.3 ± 0.1
		23.5 ± 1.8	3.8	5.9 ± 0.4	7.0 ± 0.1
	CO (13–12)	2.1 ± 0.3	0.7	2.5 ± 0.7	7.8 ± 0.2
V1318 Cyg	[C ii]	17.2 ± 0.5	...	...	
	CO (13–12)	4.0 ± 1.0	1.2	3.3 ± 0.5	8.1 ± 0.1
		6.3 ± 1.0	0.5	11.7 ± 2.4	7.8 ± 0.6

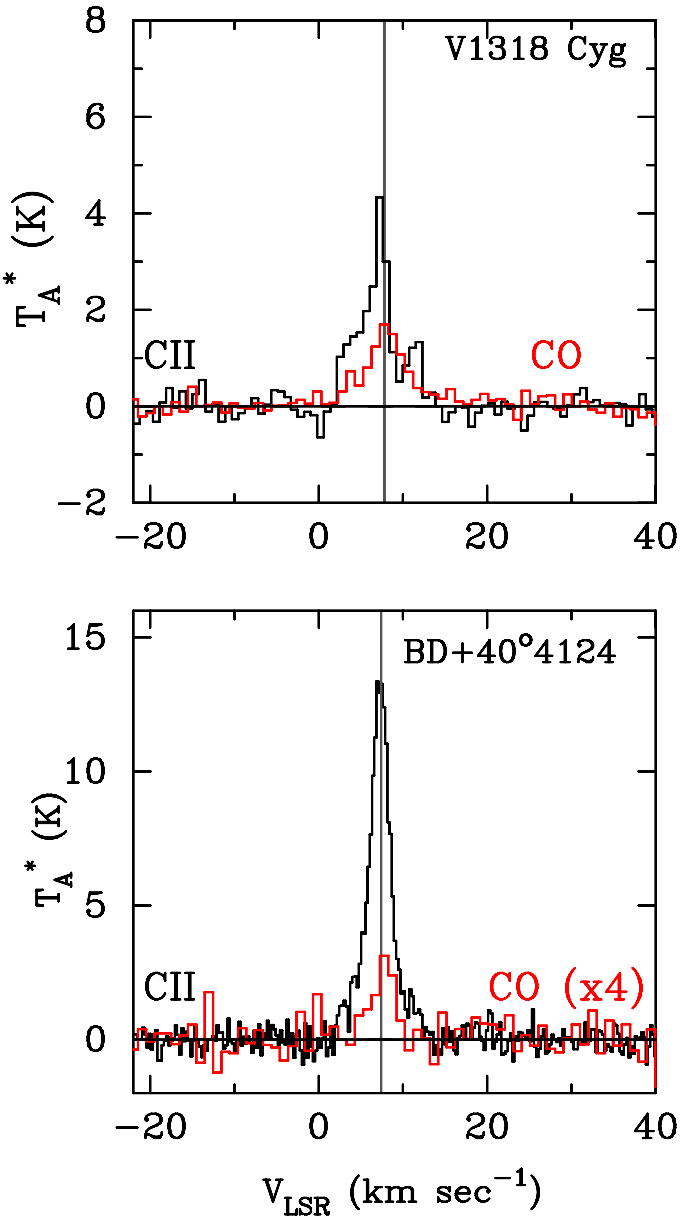

Fig. 2. Deep [C ii] and CO J = 13 → 12 spectra toward BD+40°4124 and V 1318 Cyg. [C ii] is plotted in black and the CO line profiles in red. For BD+40°4124, where the CO J = 13 → 12 line is quite faint, we multiplied the spectrum with a factor of four. The systemic velocity is marked by a vertical gray line.

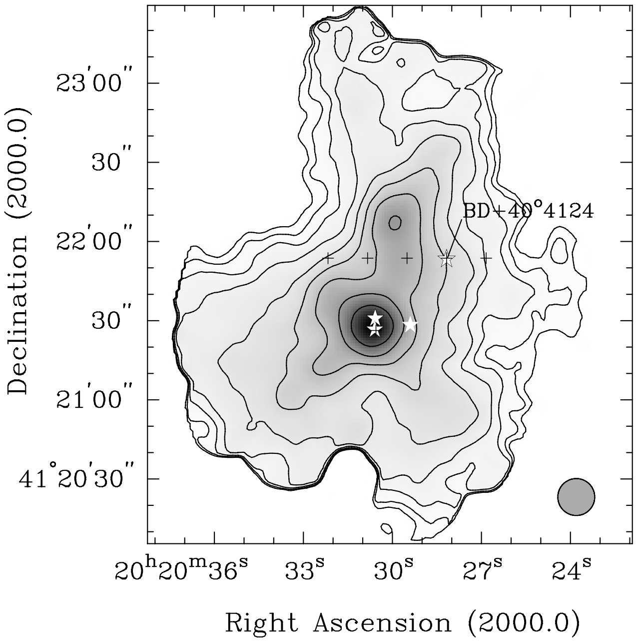

Fig. 3. 850 μm continuum image of the BD+40°4124 region from (Sandell et al. 2011). The positions observed in [C II] strip map are marked with black crosses. BD+40°4124 is indicated in the figure. The two star symbols at the peak of the 850 μm contours are V 1318 Cyg N and S, while the one to the west of them is V 1686 Cyg.

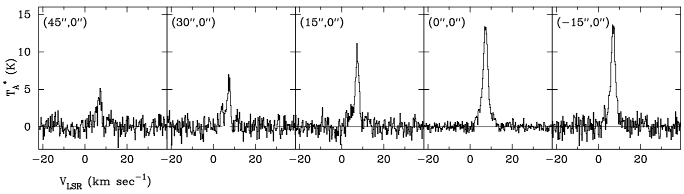

Fig. 4. Strip map in RA over BD+40°4124 in [C II] with 15″ spacing. The map suggests that [C II] peaks slightly west of the star, although the offset could be caused by the pointing.

is there any change in radial velocity or line width, suggesting that BD+40°4124 is in the foreground, and not directly connected to the molecular ridge. The extent of the [C II] emission with a full width half maximum (FWHM) of ~60″, or about the same size as the reflection nebulosity surrounding the star, confirms that the line emission originates from the reflection nebulosity, and is almost certainly photo-ionized by the UV-emission from the young B2 star. The long integration spectrum (Fig. 2) shows a broad, ~6 km s^{-1} wide pedestal (Table 1), indicating that the ionized gas is slowly expanding outward.

The CO $J = 13 \rightarrow 12$ emission, which was observed simultaneously with [C II], was also detected, but only at position (0″, 0″) toward the star itself (Fig. 2, Table 1). If the line indeed had a similar strength in the surrounding reflection nebula, it should have been detected when we took an average of the three spectra east of the star in the strip-map. However, there is no hint of CO emission in these positions in the strip-map, confirming that the CO emission comes from BD+40°4124 proper, which therefore must be surrounded by hot, molecular gas, presumably in an accretion disk.

3.2. V 1318 Cyg

We only obtained one long integration spectrum toward V 1318 Cyg (Fig. 2). CO $J = 13 \rightarrow 12$ was easily detected with $T_A^* \sim 1.7$ K. The emission is dominated by faint, broad emission extending from ∼−5 km s^{-1} on the blueshifted side to ∼+22 km s^{-1} on the redshifted side. A two-component Gaussian fit gives a FWHM of 3.3 km s^{-1} for the narrow component and 11.7 km s^{-1} for the wide pedestal (Table 1). The broad component is clearly associated with the outflow powered by V 1318 Cyg (Palla et al. 1995) and dominates the CO emission, i.e., the integrated line emission is ~1.5 times higher than the emission from the narrow component. The radial velocity of the narrow component, 8.1 km s^{-1}, agrees well with the systemic velocity of the star, 7.9 km s^{-1} determined from high spatial resolution CO $J = 2 \rightarrow 1$ observations (Looney et al. 2006) and is likely to originate in the accretion disk or the surrounding envelope.

In contrast, the [C II] emission looks quite different. At first glance it looks as if the spectrum is self-absorbed. However, there is no reason why the [C II] would be affected by self-absorption. Instead it appears that the emission is completely dominated by the outflow. Even though the CO $J = 13 \rightarrow 12$ line profile suggests that the blueshifted wing is somewhat stronger than the redshifted one, the difference is quite marginal, while the blueshifted emission completely dominates in [C II]. Most of the emission is at low velocities and we see no "high-velocity" gas in [C II]. Since we have not mapped the emission, we cannot say how extended it is. There is probably some [C II] emission throughout the outflow lobes, although the [C II] is likely to be stronger close the exciting star, see the discussion section below.

4. Discussion

4.1. [C II] emission

Our observations of [C II] in the BD+40°4124 region show that most of the [C II] emission comes from the reflection nebulosity surrounding the B2 star. Based on our strip map, we estimate the [C II] emission to have a FWHM of ~60″ similar to that of the reflection nebula. The integrated line intensity from BD+40°4124 is therefore ~40 × 10^{-15} W m^{-2} assuming a conversion factor of 1000 Jy/K between antenna temperature (T_A^*) and flux density. This estimate is very uncertain (~50%) because of the uncertainty in the size of the emitting region, but it does show that almost the entire [C II] emission observed by ISO comes from the reflection nebula illuminated by BD+40°4124. Lorenzetti et al. (2002) and Creech-Eakman et al. (2002) reported a [C II] line intensity of 56×10^{-15} W m^{-2} toward BD+40°4124. This agrees well with what van den Ancker et al. (2000) found for BD+40°4124, although they assigned a similar line intensity to V 1318 Cyg. Even though we did not map the region around V 1318 Cyg, it is quite clear from our [C II] spectrum of V 1318 Cyg (Fig. 2, Table 1) that the emission is dominated by the outflow. The line intensity toward V 1318 Cyg is only about a third of what we see toward BD+40°4124.

There are very few observations of outflows in [C II] that have both sufficient spatial and/or spectral resolution to investigate the source of the [C II] emission. The jet-like low-mass outflow HH 46 was observed with the integral field spectrometer PACS centered on the low-mass protostar (van Kempen et al. 2010). These observations show that the [C II] emission is about twice as strong in the blueshifted outflow lobe compared to the redshifted outflow lobe or the central protostar. Since there is no velocity information in these data, it is not clear whether the emission comes from low-velocity UV-heated gas in the cavity walls or whether [C II] is mixed with the molecular high-velocity gas. Unfortunately, there were no observations far away from the central source, which makes it difficult to check whether [C II] requires direct UV-excitation or whether C-shocks in the outflow would be equally efficient. The similar line strength throughout the red- and blueshifted outflow lobes suggests that in a low-mass outflow we mostly see emission from the cavity walls, which would agree with what we see toward V 1318 Cyg with GREAT, where we only see [C II] at low velocities. HIFI observations of the massive DR 21 outflow, however, show [C II] emission that is as broad as the molecular line emission (Ossenkopf et al. 2010). DR 21, however, is a high-mass star formation region with intense UV-emission.

The size of the outflow powered by V 1318 Cyg is ~55″ (Palla et al. 1995). If we assume that the [C II] emission is similar in strength as what is seen toward V 1318 Cyg, we would expect something like 15×10^{-15} W m^{-2}. This confirms that the reflection nebula surrounding BD+40°4124 dominates the [C II] emission in the large ISO beam with a minor contribution from the V 1318 Cyg outflow.

4.2. CO $J = 13 \rightarrow 12$ emission

The detection of CO $J = 13 \rightarrow 12$ emission towards BD+40°4124 is intriguing. Sandell et al. (2011) did not detect any submillimeter continuum emission towards the star with an upper limit of 35 mJy beam^{-1} at 850 μm, suggesting that the star may already have dispersed its disk. Skinner et al. (1993), however, reported a marginal detection of free-free emission at 3.6 and 6 cm, which, if real, could mean that there is still some remnant disk around the star, since free-free emission from early B-stars is generally believed to originate from photoionization of circumstellar disks (Hollenbach et al. 2000). Because we only see hot CO toward the star, it is unlikely that it would come from the surrounding envelope and it is therefore more plausible that it originates in a circumstellar disk that surrounds the star. Such a disk would have moderate inclination, because the extinction toward the star is low, $A_V \sim 3$ mag (van den Ancker et al. 1998), which agrees with the relatively narrow linewidth of the CO $13 \rightarrow 12$ line, 2.5 km s^{-1} (Table 1). Looking for high J CO emission may therefore be a good way to probe the gas in disks around early B-stars, since the gas is expected to be much hotter than in low-mass stars, owing to the much higher UV-field that illuminates and heats the disk. It would therefore be very valuable to search for hot CO in the few early B-stars that show strong evidence for a circumstellar disk, such as HD 200775, which illuminates the reflection nebula NGC 7023 (Okamoto et al. 2009), or MWC 349, which has a largely ionized disk, see e.g. Sandell et al. (2011).

In contrast, the CO $J = 13 \rightarrow 12$ emission from the deeply embedded V 1318 Cyg is much stronger than for BD+40°4124, and dominated by the hot outflow, not by the disk. The CO line has a broad pedestal with a FWHM of ≥10 km s^{-1}, which comes from the outflow and contributes to more than half of the line intensity. There is also a narrow component, which could come from the accretion disk, although it could also originate in the dense envelope that surrounds the star.

5. Conclusions

Observations with GREAT on SOFIA toward the BD+40°4124 group show that the [C II] emission seen by ISO is dominated by emission from the reflection nebula illuminated by BD+40°4124. However, we do also see [C II] emission from the outflow powered by V 1318 Cyg, which is a deeply embedded young HAEBE star ~35″ southeast of BD+40°4124. On the other hand, the high J CO emission observed by ISO is completely dominated by hot gas in the outflow from V 1318 Cyg. We also detected faint CO $J = 13 \rightarrow 12$ emission toward BD+40°4124, which suggests that the stars is still surrounded by an accretion disk.

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