Velocity-resolved [O I] 63 μm Emission in the HD 50138 Circumstellar Disk*

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Abstract

HD 50138 is one of the brightest B[e] stars and is located at a distance of ~380 pc with strong infrared excess. The star was observed in [O I] 63 μm and [C II] 158 μm with high velocity resolution with upGREAT on SOFIA. The velocity-resolved [O I] emission provides evidence for a large gas disk, ~760 au in size, around HD 50138. Whereas previous interferometric observations gave strong evidence for a hot gas and dust disk in Keplerian rotation, our observations are the first to provide unambiguous evidence for a large warm disk around the star. Herschel/PACS observations showed that the [C II] emission is extended, therefore the [C II] emission most likely originates from an ionized gas shell created by a past outflow event. We confirm the isolated nature of HD 50138. It is far from any star-forming region and has low proper motion. Neither is there any sign of a remnant cloud from which it could have formed. The extended disk around the star appears to be carbon-poor. It shows OH and [C II] emission in the optical spectrum, e.g., FeII, forbidden emission lines of predominantly low ionization metals in the optical spectrum, and a strong near or mid-infrared excess. Velocity-resolved [O I] emission most likely originates from a large warm disk. Furthermore, 13CO is enriched by more than a factor of five, confirming that the star is not a Herbig Be star. Finally, we note that our high-spectral-resolution [O I] and [C II] observations provide a very accurate heliocentric velocity of the star, 40.8 ± 0.2 km s\(^{-1}\).

Keywords: circumstellar matter – radio lines: stars – stars: emission-line, Be – stars: individual (HD 50138)

1. Introduction

HD 50138 (MWC 158) is a bright, isolated B star with strong emission lines. It was found to have variable hydrogen lines in an objective-prism survey for bright-line B-stars by Merrill et al. (1925). The spectral variability was later confirmed by Merrill (1931) and Merrill & Burwell (1933), who suggested two periods of variability, one long-term period with a periodicity of about five years and a shorter one of about 30 days. Another study by Doazan (1965) found the star to have an expanding envelope with the speed of expansion changing on a timescale of 50 days, although later studies have not been able to confirm these short-term periodicities. Instead, a recent paper (Ježábková et al. 2016) analyzing spectra over the last 20 years found two long-term periods, 8.2 ± 1.3 and 13.7 ± 2.7 years. They also found evidence for variability of the order of 50 days, consistent with the results by Doazan (1965). Some of these variabilities have been explained as a result of an outburst that possibly took place in 1978–1979 (Hutsemékers 1985) and a shell phase in 1990–1991 (Andrillat & Houziaux 1991), with yet another shell phase sometime before 2007 (Borges Fernandes et al. 2009). The star has strong infrared excess (Allen & Swings 1976) and polarimetry and spectro-polarimetry suggest it is surrounded by a circumstellar disk (Vaidya et al. 1994; Bjorkman et al. 1998; Harrington & Kuhn 2007). Mid-infrared interferometry confirms the presence of an asymmetric disk in Keplerian rotation (Ellerbroek et al. 2015) with a moderate inclination of 56° (Borges Fernandes et al. 2011). Ellerbroek et al. (2015) determined a spectral type of B7 III, in agreement with Borges Fernandes et al. (2009). The second Gaia release (Gaia Collaboration et al. 2016, 2018) provided a very accurate distance, 380 ± 9 pc. This is the distance we will adopt in this paper.

B[e]-type stars, i.e., stars that show the B[e] phenomenon, are a heterogenous group of stars of different masses and evolutionary statuses. Lamers et al. (2008) found that stars showing the B[e] phenomenon could be grouped into five classes: B[e] supergiants, pre-main-sequence B[e]-type stars or Herbig Ae/Be (HAEBE) stars, compact planetary nebulae B[e]-type stars, symbiotic B[e]-type stars, and unclassified B[e]-type stars. Lamers et al. summarized the criteria for stars showing the B[e] phenomenon as follows. They all have: “strong Balmer emission lines, low excitation permitted emission lines of predominantly low ionization metals in the optical spectrum, e.g., Fe II, forbidden emission lines of Fe II and [O I] in the optical spectrum, and a strong near or mid-infrared excess due to hot circumstellar dust.” Miroshnichenko (2007) argued that most of the unclassified B[e] stars are FS CMa stars. FS CMa stars are believed to be close binary systems, which are currently going through, or have gone through, a phase of rapid mass-transfer, resulting in mass loss and dust formation. Because the spectra of different types of B[e]-stars look the same, it is often very difficult to determine whether a star is a pre-main-sequence, main, or post-main-sequence star. Kraus (2009) showed that if the CO bands are detected, they can be used to obtain an age estimate for a star, because evolved stars should become enriched in 13CO. This method has been successfully used by Liermann et al. (2014),
who showed that several stars in their sample were evolved because of enhanced 13CO bandhead emission.

High-resolution emission-line spectroscopy is a powerful tool to probe spatially unresolved regions in circumstellar disks (see, e.g., Najita et al. 2007; Brittain et al. 2015) Velocity-resolved emission lines can provide spatial information about the gas if the disk is in Keplerian rotation and the inclination angle and mass of the central star is known. This is particularly important in the far-infrared, where there are no interferometers and where the spatial resolution of large space-based telescopes is insufficient to resolve even the largest protoplanetary disks.

Even though HD 50138 originally was classified as a classical B[e] star or as being in transition from B[e] to Be (Jaschek et al. 1993), the star shares many characteristics with Herbig Be stars. Morrison & Beaver (1995) and Grady et al. (1996) proposed that it is a pre-main-sequence (PMS) star, because it has a large infrared excess, He I and Si II show inverse P Cygni profiles, i.e., evidence for accretion, and the line profiles are consistent with a disk geometry (see also Pogodin 1997). However, it lacks one of the important criteria for Herbig Be stars, i.e., association with a star-forming region (Lee et al. 2016), making it highly unlikely that HD 50138 is a pre-main-sequence star; thus they argued that it is an FS CMa star.

We had included HD 50138 in our small GREAT survey of [O I] in circumstellar disks, based on the strong [O I] emission found in the Herschel Open Time (OT) key project DIGIT (Dust, Ice and Gas In Time; Fedele et al. 2013). However, since HD 50138 does not appear to be a pre-main-sequence star, and since the extended disk appears to be CO-deficient, we are publishing our results of this star separately.

2. Observations and Archive Data

HD 50138 ($\alpha(2000.0) = 6^h5^m33.399$, $\delta(2000.0) = -06^\circ$
57'59''5) was observed in [O I] $63$ $\mu$m with the upGREAT8 High Frequency Array (HFA) during GREAT consortium time on board the Stratospheric Observatory for Infrared Astronomy (SOFIA) on 2016 November 1. The observations were done on a 71-minute leg at an altitude of 44,000 ft (13.6 km). GREAT is a modular heterodyne instrument, with two channels, both of which are used simultaneously. For a more complete description of the instrument, see Heyminck et al. (2012) and Risacher et al. (2016). Here, we used the recently commissioned HFA together with the low-frequency channel L2. HFA targets the [O I] $3P_1 \rightarrow 3P_2$ transition at 47,74477749 THz, while L2 was tuned to the [C II] $3P_{3/2} \rightarrow 3P_{1/2}$ transition at 1.9005369 THz in the upper sideband. The HFA is a hexagonal array co-aligned around a central pixel, providing a 7 pixel array with the pixels separated by two beam widths. The HFA cryostat is cooled with a closed cycle pulse tube refrigerator and uses a novel quantum cascade laser as the local oscillator. For a more complete description of the array, see C. Risacher et al. (2018, in preparation) or Risacher et al. (2016), which describes the Low Frequency Array (LFA). The LFA has a similar design, except that it covers the $1.8$–$2.07$ THz region and uses orthogonal polarizations, therefore providing 2 $\times$ 7 pixels.

8 The development of upGREAT (German REceiver for Astronomy at Terahertz frequencies) was financed by the participating institutes, by the Federal Ministry of Economics and Technology via the German Space Agency (DLR) under grants 50 OK 1102, 50 OK 1103, and 50 OK 1104, and within the Collaborative Research Centre 956, sub-projects D2 and D3, funded by the Deutsche Forschungsgemeinschaft (DFG).

rather than 7 pixels. The main beam coupling efficiency, $\eta_{mb}$ was 0.69 for L2, and 0.65 for the central pixel of HFA. The half power beam width (HPBW) for the HFA is $\sim$6'3', while the HPBW for L2 is 14'4 at 1.9 THz. The boresight of the LFA array has an uncertainty of 1''–2''. The single-sideband system temperature was $\sim$2700 K for [C II] and around 2800–3200 K for [O I].

The backends for both channels are the last generation of fast Fourier transform spectrometers (FFTS; Klein et al. 2012), with 4 GHz bandwidth and 16384 channels providing a channel separation of 244.1 kHz (0.0385 km s$^{-1}$ for [C II]). The data were reduced and calibrated by the GREAT team. The post-processing was done using the Continuum and Line Analysis Single-dish Software package CLASS.9 We removed linear baselines, threw away a few damaged spectra, and coadded the spectra with rms weighting. The final integration times (on +off) were 44 minutes for [C II], and 38 minutes for [O I]. The final averages were resampled to 0.5 km s$^{-1}$.

Long-integration spectra of CO(3–2) and CO(4–3) were obtained with the First light APEX Submillimeter Heterodyne receiver FLASH$^+$ on the Atacama Pathfinder Experiment telescope (APEX; Güsten et al. 2006) in Chile on 2017 March 24. Both observations were done in dual beam switch mode with a 60'' chop throw. The weather conditions were marginal for CO(4–3), with $T = 1.06$, and system temperature $T_{sys} \sim 1800$ K, but were fine for CO(3–2), with $T \sim 0.23$, and $T_{sys} \sim 270$ K. The total integration times were 1.3 and 2.6 hr for CO(3–2) and CO(4–3), respectively. There is no sign of any CO emission.

A near-infrared high-spectral-resolution (R $\sim$ 50,000) spectrum of HD 50138, covering the 2.276–2.326 $\mu$m wavelength range (containing the bandhead of CO 2-0 overtone emission) was taken with the VLT Cryogenic high-Resolution InfraRed Echelle Spectrograph (CRIRES$^{10}$; Käfli et al. 2004) on 2009 November 5. Adaptive Optics were used to optimize the signal-to-noise ratio and spatial resolution of the observations. The observations were made with a slit width of 0''4, with the slit oriented along the parallactic angle. The spectrum was reduced with the ESO automatic pipeline, and corrected for telluric and heliocentric velocity.

We also analyze a spectrum obtained with NIRSPEC (McLean et al. 1998), a high-resolution echelle spectrograph on the Keck II telescope on 2009 October 9. This M-band spectrum of HD 50138 was observed with a 0''43 $\times$ 24'' slit, which provides a resolution, $R \sim 25000$ (FWHM $\sim 12.5$ km s$^{-1}$). The two spectral orders cover the wavelength range 4.65–4.78 and 4.96–5.1 $\mu$m. These wavelength ranges include the CO fundamental ($\nu = 1 \rightarrow 0$) rovibational transitions R(0–1) and P(1–12, 30–40). The data were corrected for atmospheric absorption using standard stars and wavelength-corrected using telluric emission lines. For further details on data reduction, see Salyk et al. (2009). Salyk et al. (2011) used the data in their study of molecular emission from protoplanetary disks, but did not show a spectrum.

We retrieved three photometry observations performed with the Photoconductor Array Camera and Spectrometer (PACS) instrument on the Herschel Space Observatory from the Herschel data archive. These were all done in the 70 $\mu$m and

9 CLASS is part of the Grenoble Image and Line Data Analysis Software (GILDAS), which is provided and actively developed by IRAM, and is available at http://www.iram.fr/IRAMFR/GILDAS.

10 http://www.eso.org/sci/facilities/paranal/instruments/crires/
160 \, \mu m bands (AOR-ID 1342228369, 1342228916, and 1342250822). All three data sets are consistent within observational errors and give flux densities of 7.50 ± 0.05 Jy and 1.40 ± 0.04 Jy at 70 and 160 \, \mu m, respectively.

3. Results and Analysis

Both [O I] and [C II] were detected with high signal-to-noise toward HD 50138 (Figure 1). The [O I] line is not well fit with a single Gaussian, because it shows broad faint line wings at low levels; see Table 1. A two-component fit gives the same integrated intensity as a simple integration over the velocity range covered by the line, 16 K \, km s\(^{-1}\). This is somewhat low compared to what we would expect to see with GREAT from the observed PACS line intensity, 24 ± 1 \times 10^{-16} \, W \, m^{-2}, which corresponds to \(21.4 \, K \, \text{km s}^{-1} (T_{\text{mb}})\), suggesting that we were probably off-source by 1″–2″. The high critical density of [O I], \(5 \times 10^{5} \, \text{cm}^{-3}\) (collision partner H\(_2\), at \(T_k \sim 120 \, K\), the rate coefficient from Jaquet et al. 1992), requires that the line originates in dense PDR gas. Shock excitation can be ruled out because there is no evidence for strong shock emission toward the star. Since the color excess, \(E_{B-V}\) toward HD 50138 is at most 0.15, with about half of it, 0.08 mag, being interstellar (Borges Fernandes et al. 2009), the reddening from circumstellar material is small, \(\sim 0.2\) mag (assuming an average galactic extinction law of 3.1), and the [O I] emission cannot originate in a circumstellar shell. The only plausible explanation is that the [O I] emission comes from a disk surrounding the star, especially since the large line width, 6.2 km \, s\(^{-1}\), and symmetrical line profile are hard to explain except by rotational broadening in a Keplerian disk. The disk-like morphology of the circumstellar environment surrounding HD 50138 is well established both from polarimetric and spectropolarimetric observations (Vaidya et al. 1994; Bjorkman et al. 1998; Harrington & Kuhn 2007), as well as from interferometric near- and mid-IR observations (Borges Fernandes et al. 2009; Monnier et al. 2009; Ellerbroek et al. 2015; Kluska et al. 2016; Lazareff et al. 2017). Ellerbroek et al. (2015), who observed HD 50138 with high spectral and spatial resolution in the Br\(\gamma\) line with AMBER on VLTI, found that they could model their data with a thin Keplerian disk and a spherical halo on top of a Gaussian continuum. Their model with a 0.6 au disk in Keplerian rotation, with the continuum (hot dust) being more extended, does a relatively good job of explaining most of their observed features. Additional support for a Keplerian disk comes from the fundamental CO lines presented in this paper. The shape of the broad P-branch lines (Figure 2) suggest that they would resolve into clear double-peaked profiles if observed with higher spectral resolution. The bottom panel in Figure 2 shows that the line profile can be well fit with a Gaussian with two velocity components; a blueshifted one at \(+35.1 \, \text{km s}^{-1}\) and a redshifted one at \(+55.9 \, \text{km s}^{-1}\), with line widths of 19 and 23 \, \text{km s}^{-1}, respectively. Both Br\(\gamma\) and CO show asymmetric line profiles, while the [O I] line appears perfectly symmetric (Figure 1).

If we adopt the stellar mass, \(6 \, M_\odot\), a disk inclination, 56° (Ellerbroek et al. 2015), and take the rotational velocity as FWHM/2, i.e., \(v_{\text{rot}} = 3.1 \, \text{km s}^{-1}\) (Table 1), we find that the [O I] emission originates within a 380 au radius. This sounds entirely plausible. The broader, faint component comes from hot gas in the inner part of the disk, where one also sees CO emission. Although one would naively expect the [O I] profile to be double-peaked, the typical signature of a Keplerian disk, there is no evidence for a central dip in the [O I] spectrum. This suggests that the [O I] emission is optically thin. The same is true for well studied bona fide Keplerian disks like HD 100546 and HD 97048, which also show single-peaked [O I] 63 \, \mu m line profiles (R. Güsten et al. 2018, in preparation).

The PACS observations by Fedele et al. (2013) show that the [C II] emission is extended at the 20″ level. Therefore, most of the [C II] emission is likely to originate in a low-density shell created by a past ejection event, although there could be some contribution to the observed [C II] emission for the ionized surface layers of the circumstellar disk. Toward HD 50138, the observed velocity, \(v_{\text{LSR}} = 22.8 \, \text{km s}^{-1}\), is the same for both [O I] and [C II](Table 1), corresponding to a heliocentric velocity, \(v_{\text{rad}} = 40.8 \, \text{km s}^{-1}\). This velocity differs somewhat from what has been commonly used, \(\sim 35 \, \text{km s}^{-1}\) (see e.g., Borges Fernandes et al. 2009; Ellerbroek et al. 2015), but is in good agreement with Jerábková et al. (2016): \(v_{\text{rad}} = 40 \pm 4 \, \text{km s}^{-1}\). Since we have a much higher velocity

### Table 1

| Line    | \(\frac{\Delta V}{T_{\text{mb}}} (\text{K km s}^{-1})\) | \(T_{\text{mb}}^0 (K)\) | \(v_{\text{LSR}} (\text{km s}^{-1})\) |
|---------|---------------------------------|-------------------|-------------------------------------|
| [O I]   | \(11.3 \pm 1.2\)               | 1.70              | \(06.2 \pm 0.3\)                     |
|         | \(4.7 \pm 1.2\)                | 0.29              | \(15.5 \pm 2.8\)                     |
|         | \(2.2 \pm 0.2\)                | 0.60              | \(05.2 \pm 0.4\)                     |
| [C II]  | \(2.2 \pm 0.2\)                | 0.60              | \(22.90 \pm 0.20\)                   |
| CO(4–3) | \(<0.23\)                      | ...               | ...                                  |
| CO(3–2) | \(<0.04\)                      | ...               | ...                                  |

**Note.** For CO(4–3) and (3–2), both of which are non-detections, we only give the 3σ upper limit of the line integral. Upper limits are computed with a 4 km s\(^{-1}\) velocity range over a 20 km s\(^{-1}\) velocity range centered on the stellar velocity.

Figure 1. CO(3–2), [O I], and [C II] spectra toward HD 50138. The CO(3–2) spectrum was resampled to a velocity resolution of 1 km s\(^{-1}\) and scaled by a factor of 5, as indicated in the figure (x 5). There is no sign of CO emission in the spectrum. The CO(4–3) spectrum, which is much noisier (see Section 2), is not shown. The [C II] and [O I] spectra were offset in temperature and resampled to a velocity resolution of 0.5 km s\(^{-1}\). The two Gaussian components (Table 1) are plotted on top of the [O I] spectrum in red (broad component) and green (“narrow” component). The gray vertical line marks the fitted line center, 22.8 km s\(^{-1}\). All spectra are labeled.
The velocity scale is in the two velocity components, while the green and the blue lines show the average of all the spectra in the top panel. The red lines show the sum of other to improve clarity. Bottom panel: two-component Gaussian fit to the observed line profile. The spikes in the spectra are from imperfect cancellation of telluric lines. There is no sign of the CO overtone bands.

Figure 2. Top panel: NIRSPEC spectrum covering the wavelength range 4.65–4.78 μm. The blue vertical lines show 12CO $v = 1 \rightarrow 0$ transitions, while the green dashed lines show 13CO $v = 1 \rightarrow 0$. The red marks the Hα emission line. The purple is Pfβ. Middle panel: selected CO P transitions from the NIRSPEC M-band spectrum. Regions affected by telluric absorption have been blanked out. The spectra have been continuum-subtracted and are offset relative to each other to improve clarity. Bottom panel: two-component Gaussian fit to the average of all the spectra in the top panel. The red lines show the sum of the two velocity components, while the green and the blue lines show the individual velocity components. The velocity scale is in $V_{lsr}$.

resolution than what can be achieved in the optical, our derived systemic velocity is much more accurate.

Fedele et al. (2013), who did complete range scans of HD 50138, did not detect any CO emission, which is often seen in disks around HAEBE stars; see also Meeus et al. (2013), who analyzed CO transitions from the same data set. Fedele et al. (2013), however, did detect several OH transitions. From the detected OH transitions and upper limits to non-detections they derived an excitation temperature of 130 K and an OH column density of $2 \times 10^{15}$ cm$^{-2}$. The relatively cold and low-density molecular gas can readily explain why high-J CO was not detected by Herschel, but it should be easy to detect in lower-J CO lines from the ground. Yet our deep APEX observations of CO(3–2) and (4–3) do not show any hint of CO emission, nor did Kama et al. (2016) detect the CO(6–5) transition using the same telescope. If we assume that the excitation temperature is 100–200 K, we find 3σ upper limits of the CO column density from CO(3–2) of $2.9 \times 10^{13}$ cm$^{-2}$ and $1.8 \times 10^{13}$ cm$^{-2}$, for an excitation temperature of 100 K and 200 K, respectively. If the temperature was as low as 50 K, the upper limit from CO(3–2) would be $3.8 \times 10^{14}$ cm$^{-2}$. For CO(4–3) the corresponding upper limits are $6.1 \times 10^{13}$ cm$^{-2}$ (100 K) and $9.2 \times 10^{13}$ cm$^{-2}$ (200 K). The CO(6–5) upper limit (Kama et al. 2016) provides even fewer constraints to the CO column density, $<2 \times 10^{14}$ cm$^{-2}$. Therefore for warm (100–200 K) molecular gas the CO column density is $<3 \times 10^{13}$ cm$^{-2}$. This is unusual, because CO is always the most abundant molecule in protoplanetary disks (next to H$_2$, which cannot be observed in the radio regime due to lack of dipole moment), while OH is one to several orders of magnitude less abundant (Bergin 2009; Visser et al. 2011). If we assume that [O I] comes from the same part of the disk as OH, i.e., $T_{ex} = 130$ K, then our observed line intensity, 11.3 K km s$^{-1}$, (Table 1) gives an [O I] column density, $N([O I]) \sim 7 \times 10^{13}$ cm$^{-2}$, which is about three times larger than the OH column density, suggesting that the outer disk may have a high fraction of atomic gas.

There is no sign of CO bandhead emission in the CRIRES spectrum (Figure 3), nor was it seen in a recent X-shooter spectrum (M. Benisty 2017, personal communication). The lack of CO bandhead emission rules out any hot (2000–3000 K) CO gas, which is sometimes seen in Herbig Ae/Be stars (Ilee et al. 2014; van der Plas et al. 2015), including the unusual B0 star MWC 349A (Kraus et al. 2000). However, there is clearly warm CO in the inner disk. The NIRSPEC M-band spectrum (Figure 2) shows that the fundamental rovibrational 12CO lines are rather strong. The modeling done by Salyk et al. (2011) give a high column density, $N$(CO) = $1.3 \times 10^{14}$ cm$^{-2}$, and a gas temperature of 725 K. The size of the CO-emitting region predicted by their modeling is $\sim 2$ au, while the size derived from the observed line width is somewhat larger, $\sim 12$ au. This makes the warm CO too diluted to be detected by Herschel or any large ground-based radio telescope.
The $^{13}$CO lines appear quite strong relative to $^{12}$CO; see Figure 2. We therefore modeled the data to see whether the $^{13}$CO isotope has a normal interstellar medium (ISM) isotope ratio or whether it is enhanced. The model used is a simple slab model (see Salyk et al. 2009, for more details) assuming a flat disk that has a $^{12}$CO column density of $10^{18}$ cm$^{-2}$, a temperature of 1000 K, and an emitting area of $\pi \times (2.45 \text{ au})^2$, or 18.9 au$^2$—arbitrarily scaled to match the data. This model implicitly assumes that the $^{12}$CO and $^{13}$CO are emitted from the same region, and have the same temperature and emitting area. It seems that the ISM $^{12}$C/$^{13}$C ratio, 70, does not match the data, while a $^{12}$C/$^{13}$C ratio of 10 provides a much better fit, suggesting that $^{13}$CO is enhanced by at least a factor of 5 (Figure 4).

Since the PACS beam size at 160 $\mu$m is 11"/2 compared to $\sim$5' for IRAS at 100 $\mu$m, we can compare the IRAS flux densities to those of PACS. This way one can verify if there is any extended emission surrounding HD 50138, which is not seen by PACS. We performed a graybody fit to the SMA data (Lee et al. 2016), the PACS 160 and 70 $\mu$m photometry (this paper), and IRAS, WISE, and MSX photometry. This graybody fit gives a dust temperature of 370 K, a radius of $\sim$500 au (not well constrained), and a very small dust emissivity, 0.12, suggesting large dust grains. This fit is shown in Figure 5. We can see that the hot dust close to the star starts to dominate at $\sim$10 $\mu$m, which is also seen in the SED plot by Lee et al. (2016). The color-corrected IRAS flux densities agree well within measurement errors at 25 $\mu$m and 60 $\mu$m with what we derive from our fit, 39.2 Jy and 9.4 Jy at 25 $\mu$m and 60 $\mu$m, respectively, while the IRAS flux densities are 44.3 $\pm$ 1.9 Jy and 10.5 $\pm$ 0.8 Jy, suggesting that there is no residual dust cloud around the star. This analysis shows that the warm dust emission has an angular extent similar to the size we deduce from [O I]. Although the SMA observations did not resolve the dust emission at 1.3 mm (Lee et al. 2016), our analysis shows that it could most likely be resolved by ALMA. It might even be possible to detect warm CO from the inner disk by ALMA in band 9 or 10.

4. HD 50138 Is Not a Herbig Be Star

Lee et al. (2016) provided convincing arguments that HD 50138 is not a HAEBE star. In particular, they could not find any star-forming region in the vicinity of the star from which the star could have formed. To confirm the isolated nature of the star we checked the CO images from the all-sky Planck$^{11}$ mission, which provides an unprecedented sensitivity to find molecular clouds anywhere in our Galaxy. These confirm that HD 50138 is isolated. The nearest molecular cloud is $\sim$0.5$^\circ$ to the north. This cloud is possibly connected to G217.93−02.07, which would place it at a distance of $\sim$2 kpc (Elia et al. 2013). This distance is much larger than the distance to HD 50138, clearly demonstrating that HD 50138 is not associated with this cloud. There is a small cold cloud detected at the 5$\sigma$−6$\sigma$ level $\sim$18$^\circ$ west of the star listed in the Planck catalog of Galactic Cold Clumps, although it is unlikely that it has any association with HD 50138. The second Gaia release (Gaia Collaboration et al. 2016, 2018) showed that the proper motion is small [(3.6, −3.7) mas yr$^{-1}$] or $\sim$8.5 km s$^{-1}$. The radial velocity is therefore the dominant velocity component. Since the extinction is only 0.4 mag, there is nothing along the line of sight from which it could have formed. In addition, the PMS lifetime for a 6 $M_\odot$ star is rather short, under the assumption that the star could not have wandered very far.

It is also well documented that HD 50138 has undergone several shell events (Jerábková et al. 2016), which distinguishes it from HABE stars, which show no such activity. The disk around HD 50138 differs from disks around HAEBE stars. As shown in this paper there is no detectable molecular gas except for OH in the extended warm disk where we see [O I]. This is very unusual. Searches for CO show that it is one to two orders less abundant than OH, while the inverse is the case for protoplanetary disks. We have detected CO, but only in the hot inner disk. The graybody fit (Section 3) suggests that there

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11 Planck (http://www.esa.int/Planck) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states and led by Principal Investigators from France and Italy, telescope reflectors provided through a collaboration between ESA and a scientific consortium led and funded by Denmark, and additional contributions from NASA (USA).
is very little cold dust in the disk. There are certainly HAEBE disks without cold dust like LkHα,101 and MWC 297. This is shown by detailed SED analysis of high spatial resolution radio, millimeter, and submillimeter emission (Sandell et al. 2011), which confirms that all the emission through the submillimeter wavelength regime is still completely dominated by thermal emission from an ionized disk wind. However, these are all early B-stars with strong FUV radiation. Cold dust should survive in the midplane of a disk around a B7 star. In this case, the disk appears to be dominated by hot ionized gas and warm atomic gas.

The disk has some unusual characteristics. It appears to be asymmetric (Ellerbroek et al. 2015; Kluska et al. 2016). Near-infrared interferometric monitoring on the VLTI (Kluska et al. 2016) shows strong morphological changes in the innermost part of the disk on a timescale of a few months. Kluska et al. (2016) find that they can reproduce the variability by a model of a disk with a bright spot in the disk, but they cannot reproduce the variability with a binary model. There is very little cold dust in the disk and the outer disk appears carbon-deficient. It has OH but no detectable CO, yet the disk is rather extended (720 au). The [O I] observations show that it has dense warm atomic gas similar or larger than the amount of OH. However, our modeling of the M-band fundamental CO transitions shows that $^{13}$CO is enriched by more than a factor of five, which excludes it from being a PMS star, since such an enhancement requires a significant enrichment of $^{13}$C (Kraus 2009).

In short, we agree with Lee et al. (2016) that HD 50138 is not a pre-main-sequence star.

5. Summary and Conclusions

There is firm evidence that the circumsteller material surrounding HD 50138 has a “disk-like” morphology. Furthermore, Ellerbroek et al. (2015), performing high spectral and spatial imaging of the Brγ line, found that the hot inner disk is in Keplerian rotation around the central star. This is also supported by the CO fundamental rovibrational spectra presented in this paper. Because of the high critical density of the [O I] 63 μm line, the [O I] emission must originate in the disk. If we assume that the outer disk also follows Keplerian rotation, the size of the [O I] disk is about 760 au based on the observed line width of the [O I] emission. Where [C II] originates is unclear. Since PACS observations show that the [C II] emission is extended, most of the emission must originate in a lower density shell surrounding the star, although we cannot exclude that some of the emission could come from the ionized surface layers of the disk.

We find that the gas in the extended disk surrounding HD 50138 is largely ionized and atomic and the hot dust completely dominates the dust emission. The outer disk has rather unusual chemistry. Fedele et al. (2013) detected several transitions of OH in their PACS range scan, but no high-J CO emission. Long-integration APEX observations failed to detect CO(3–2) and CO(4–3), indicating that CO is at least an order of magnitude less abundant than OH in the extended disk. In protoplanetary disks CO is always the most abundant molecule and OH is one or several orders of magnitudes less abundant. We find that $^{13}$CO is enriched by more than a factor of five, which excludes it from being a PMS star, since such an enhancement requires a significant enrichment of $^{13}$C in the circumstellar gas, as shown by Kraus (2009).

We agree with Lee et al. (2016) that HD 50138 is not a HAEBE star. It must be a main-sequence star or post-main-sequence star, and is most likely an FS CMa star, and we provide further support for the isolated nature of the star.

Our high-spectral-resolution [O I] and [C II] observations provide a very accurate radial velocity of the star, 40.8 ± 0.2 km s$^{-1}$, which is much more accurate than what can be obtained from optical spectroscopy.

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