HERSCHEL PHOTOMETRY OF DISKS AROUND LOW-MASS STARS IN THE R CrA CLOUD*

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ABSTRACT

We report photometric results from a subset of a *Herschel*–PACS program to observe cool dust in disks around low-mass stars as a complement to our earlier program to measure far-infrared emission from brown dwarfs. In this latest study we observed five low-mass objects in the nearby R Corona Australis region and detected at least three at 70 μm . Using a Monte Carlo radiative transfer code we have investigated the disk masses and geometry based on detailed spectral energy distribution (SED) modeling, and we compare these new results to those from our earlier larger sample of brown dwarfs. In particular, our SED analysis for these five objects shows again that disk geometries of brown dwarfs or low-mass stars are generally similar to their higher mass counterparts like T Tauri disks, but the range of disk mass extends to well below the value found in T Tauri stars.

Key words: brown dwarfs – protoplanetary disks – stars: formation

Online-only material: color figures

1. INTRODUCTION

Circumstellar (and sub-stellar) disks are common around young objects from a few solar masses down to objects well into the range of brown dwarfs. Most of the mass in these disks is in the outer regions where temperatures are relatively cool, particularly around the lowest luminosity objects. The total mass of dust is best studied at submillimeter and millimeter wavelengths where it is almost certainly optically thin. The total emission flux levels, though, are brighter at far-infrared wavelengths where the emission is also sensitive to the disk geometry. Furthermore, even though the disks are likely to be optically thick through the mid-plane out to wavelengths of several hundred microns, modeling has shown (e.g., Harvey et al. 2012a, 2012b, hereafter Papers I and II) that the disk masses around low-mass stars and brown dwarfs can be roughly estimated from the far-infrared flux levels.

In this paper we report results from a fraction of a program on far-infrared disk emission that was completed in the final weeks of the cryogenic lifetime of the *Herschel* mission (Pilbratt et al. 2010). Below we describe the sample objects that were successfully scheduled and observed and the instrumental parameters and mode used for the observations. The observed objects are all in the relatively compact Coronet cluster in the nearby R Corona Australis region at a distance of 138 pc (Ortiz et al. 2010). This cluster is also an ideal region to study low-mass young stars because of the relatively low sky background emission. Sicilia-Aguilar et al. (2013) have studied the higher mass population of young stars surrounded by disks in this region with *Herschel*–PACS. There is one object in common between that program and ours, G87, but they were only able to obtain an upper limit to the flux at 100 μm due to the relatively short integration times used.

Our program was modeled closely after our extensive set of observations and analysis of disk emission around 47 sub-stellar and very low-mass stellar objects described in Paper II. Therefore, following the description of the observations, we briefly summarize the data analysis and modeling, but refer the reader to the more complete description in Paper II. The main results of this new study are summarized in Section 5 where we compare the results on the five R CrA objects newly observed with the larger sample from Paper II.

2. SAMPLE, OBSERVATIONS, AND DATA REDUCTION

Table 1 lists the observed sample of low-mass stars and one brown dwarf. Although our full object list included low-mass stars in other nearby star-forming regions, the only observations that could be scheduled before the end of cryogenics for *Herschel* were these five in the R Corona Australis cloud (Neuhäuser & Forbrich 2008).

Our program, OT2_pharve01_6, was modeled after our earlier program described in Paper II. The observations used the PACS “mini-scan-map” mode (Poglitsch et al. 2010) that allows high and relatively uniform sensitivity over an area of about $60'' \times 90''$ in the center (within 80% of peak coverage). Table 1 lists the parameters for all the observations reported here including the OBSIDs. The uncertainties at 160 μm were generally determined by the level of diffuse emission in the images as low-pass-filtered in the same way as the detected sources.

The data were processed as described in Paper II but using the *Herschel* Interactive Processing Environment, HIPE version 8.1. The mosaicked images are shown in Figure 1. As in Paper II, we used the point-spread-function-fitting photometry tool, *c2dphot* (Harvey et al. 2006; Evans et al. 2007) based on the earlier DOPHOT tool (Schechter et al. 1993). We estimated uncertainties by using our psf-fitting photometry tool on blank sections of sky as described in Paper II. At 160 μm the flux uncertainties were dominated by structure in the diffuse emission on the scale of compact sources.

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Figure 1. Images of five program objects; top row is 70 μm , bottom row is 160 μm . The dashed circles centered on the nominal source positions are 30'' in diameter. (A color version of this figure is available in the online journal.)

Table 1
Source Summary (Program ID = OT2_pharve01_6)

Object	R.A./Decl. Center (J2000) (h m s) (° ' ")	OBSIDs	Obs. Date	F_{ν} 70 μm (mJy)	F_{ν} 160 μm (mJy)	Sp. Type
CrA 444	19 00 45.3 –37 11 48	1342269684/85	2013 Apr 9	23.1 ± 1.3	22.0 ± 4.0	M8.5
ISO CrA 123	19 01 16.3 –36 56 28	1342269743/44	2013 Apr 9	20.9 ± 1.0	<35	M5.0
G94	19 01 29.0 –37 01 48	1342269739/40	2013 Apr 9	5.0 ± 1.0	<30	M3.5
G87	19 01 32.3 –36 58 03	1342269741/42	2013 Apr 9	15.4 ± 0.9	<50	M3.5
ISO CrA 143	19 02 12.0 –37 03 09	1342269737/38	2013 Apr 9	3.9 ± 1.0	<15	M4.5

3. OBSERVATIONAL RESULTS

Figure 1 shows images at both observed wavelengths for the five program objects. Our observed flux densities are listed in Table 1. The upper limits in Table 1 were derived by estimating the brightest undetectable flux level for a compact source at the object position. These values are roughly equivalent to $\sim 3\sigma$. For objects with a possible detection, we report the flux derived from the psf-fit and the uncertainty derived using several psf-fit positions in blank portions of the image.

All our program objects have been observed at shorter wavelengths by some or all of the Two Micron All Sky Survey (Skrutskie et al. 2006), DENIS, and *WISE* (Wright et al. 2010) surveys, numerous *Spitzer* programs using IRAC and MIPS, as well as four with the Infrared Spectrograph (IRS) instrument on *Spitzer*. Therefore, we have very complete spectral energy distribution (SED)’s for all the sources, and as discussed below, can employ model fitting to derive limits on physical parameters of the circumstellar disks. The photometric points in the SED figures later were taken from these surveys, the *Spitzer* Gould Belt study by Peterson et al. (2011), and the US Naval Observatory catalog.

4. RADIATIVE TRANSFER MODELING

In Paper II we presented disk modeling results for 47 brown dwarfs and very low-mass stars. Although there is significant degeneracy in derived parameters from such modeling, we were able to constrain the circum-object disk masses and

geometry for the cases with good SED coverage. In this latest study we modeled the disks around all five objects using the three-dimensional (3D) Monte Carlo radiative transfer code discussed already in Paper II, MC3D described by Wolf et al. (1999) and Wolf (2003). We have assumed a single, uniform grain composition, and we have not included the *Spitzer* IRS data in the area of the silicate feature because this feature is probably due to optically thin dust in the disk atmospheres, e.g., Olofsson et al. (2009). We assumed a photospheric temperature based on the observed spectral types and used NextGen stellar atmosphere models (Hauschildt et al. 1999; Allard & Hauschildt 1995) to characterize the stellar input spectra. As in Paper II we modeled each SED with a parametric disk. The assumed dust density distribution had a Gaussian vertical profile $\rho(r, z) = \rho_0(r) \exp(-z^2/2h^2(r))$, which is valid for a hydrostatic, vertically isothermal, non-self-gravitating disk. The dust surface density was assumed to follow a power-law distribution, $\Sigma(r) = \Sigma_0 (r/r_0)^{-p}$, and the scale height $h(r) = h100 (r/r_0)^{\gamma}$ where r is the radial coordinate in the equatorial plane. The parameter $h100$ is the scale height at $r_0 = 100$ AU for comparison with previous BD and T Tauri disk models. The scale height parameters, γ and $h100$, are not calculated from assumptions of hydrostatic equilibrium but are free parameters in the modeling. The disk’s inner and outer radii are r_{in} and r_{out} . The central star is a uniformly radiating sphere. We assumed dust properties identical to those used by Sicilia-Aguilar et al. (2013), i.e., 75% amorphous silicate grains and 25% carbon, and also assumed a gas-to-dust ratio of 100 by

Figure 2. Observed spectral energy distributions and an example well-fitting model for each object. The upper limits shown are from our 160 μm data and from the 100 μm measurement of G87 by Sicilia-Aguilar et al. (2013). The model parameters are given in Table 2. The dashed lines show the model photosphere, and the solid lines show the complete fitted SED.

(A color version of this figure is available in the online journal.)

Figure 3. Probability distributions for model parameters for CrA 444. The top row shows the inner disk radius in units of the sublimation radius, the total disk mass in solar masses, and the disk flaring index, γ . The bottom row shows the surface density exponent, p , the disk scale height parameter $h100$, and the disk inclination.

Figure 4. Probability distributions for model parameters for *ISO CrA 123*. **Figure 5.** Probability distributions for model parameters for *G94*.

Figure 6. Probability distributions for model parameters for G87.

Figure 7. Probability distributions for model parameters for ISO CrA 143.

mass for the mass calculation. We assumed a size distribution $n(a) \propto a^{-3.5}$ with $a_{\text{min}} = 0.1 \mu\text{m}$ and $a_{\text{max}} = 100 \mu\text{m}$, though no significant conclusions about grain size distribution could be drawn from our modeling.

As discussed in [Paper II](#), the model SED does not depend significantly on the choice of outer radius because the bulk of the far-IR radiation arises from dust inside a radius of 20 AU. Therefore, the outer radius was fixed for all the models

Table 2
Parameter Values of the Best-fit SED Models

Object	T_{eff} (K)	Luminosity ($L_{\odot}$)	A_v (mag)	r_{in}^a (AU)	M_{disk} ($10^{-6} M_{\odot}$)	γ^b	p^c	$h100^d$ (AU)	Inclination ($^{\circ}$)
CrA 444	2600	0.015	1.1	0.086	31.6	1.15	1.0	17	15
<i>ISO</i> CrA 123	3100	0.016	1.0	0.0093	100	1.10	0.5	20	60
G94	3300	0.06	1.2	0.019	3.16	1.10	0.5	2	30
G87	3300	0.10	13.5	0.024	1.0	1.15	1.5	5	30
<i>ISO</i> CrA 143	3200	0.016	2.1	0.043	1.0	1.20	1.5	8	45

Notes.

^a Inner disk radius.

^b Disk flaring index.

^c Surface density gradient.

^d Disk scale height at 100 AU.

at 100 AU. The choice of outer radius also makes only a small difference in the probable values of most other disk parameters.

5. DISCUSSION AND SUMMARY

Our modeling results are displayed in Figures 2–7. Figure 2 shows the observed SEDs of the five low-mass objects together with an example of a well-fitting model for each. The parameters for these models are given in Table 2. We emphasize, though, that a substantial range of models provides a good fit to the SEDs over the observed wavelength range. This fact is illustrated in Figures 3–7 that show the probability distributions for several model parameters for each object.

In Paper II we found that there was a reasonably good correlation between the $160\text{ }\mu\text{m}$ flux density and the model-derived disk mass. For these additional five objects in R CrA, we see that the highest mass, and best-defined, disk is that around CrA 444 which also has the only bona-fide detection at $160\text{ }\mu\text{m}$. In Paper II we also found that it was difficult to constrain other parameters of the disk properties, other than the fact that the disk inner radii appeared to be consistent with the expectation that they were defined by the dust sublimation radius. Our new results are completely consistent with this interpretation with the exception of the known binary, G94 (Romero et al. 2012), where the probability distribution for the disk inner radius displays a bi-modal shape with a minimum at a value of about 10 times the dust sublimation radius. The companion is at a separation of $0''.5$, so the weak disk emission that we detect is likely around the primary only, and as shown by Bouwman et al. (2006), the inner disk regions in such objects are likely short-lived. The remaining disk parameters show relatively broad distributions and are also completely consistent with the range of values found in the larger sample in Paper II. The probability distributions for the disk masses suggest likely masses for the two brightest objects of order a few $\times 10^{-5} M_{\odot}$, but only of order $10^{-6} M_{\odot}$ for the three fainter objects, G-87, G-94, and *Infrared Space Observatory* (ISO) CrA 143. Interestingly the latest spectral type source, CrA 444 at M8.5, has the highest likely model disk mass. Sicilia-Aguilar et al. (2013) have also observed G87 at $100\text{ }\mu\text{m}$ with *Herschel* and modeled the SED. Their derived disk mass, scale height, and flaring index are all reasonably consistent with our modeling, though their best-fit model used an inner-disk hole consistent with the interpretation as a transition disk. Given the uncertainties in stellar and sub-stellar atmosphere models at

these wavelengths, this difference in conclusions does not seem significant.

In summary, these five objects exhibit disk properties very similar to those observed in our larger survey (Harvey et al. 2012a, 2012b). The masses, in particular, generally appear to be in the range of 10^{-6} – $10^{-4} M_{\odot}$, and the disk geometries, like those described in our earlier papers, are similar to those derived from modeling of T Tauri stars.

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