The circumstellar environments of high-mass protostellar objects

II. Dust continuum models

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Abstract. We analyse the dust continuum emission seen towards a sample of candidate high-mass protostellar objects, modelling the cores we recently observed at 850 μm with a one-dimensional radiative transfer code. Fitting radial slices in a range of directions across sources, we identify a number of objects that have non-spherical density profiles and show that for such sources fitting the azimuthal averaged emission produces erroneous estimates of the source properties. We find the majority of cores can be successfully modelled using envelopes of power-law density structure (where $\rho \propto r^{-\alpha}$), finding a mean power-law index of $\bar{\alpha} = 1.3 \pm 0.4$. These envelopes extend considerably further, are more dense, and have a more shallow density profile than those bearing low-mass protostars. The majority of best-fit models have a SED resembling the cold-component dust bodies previously proposed for the sample, implying the short wavelength emission seen towards the HMPOs either originates from a separate hot dust component(s), or involves mechanisms such as accretion disks, stochastic heating and/or optically thin cavities not included in the radiative transfer model. We find evidence of smaller dust-free cavities towards some pre-UCHII sources. The modelling indicates a correlation between α and optical depth, suggesting that the densest cores also tend to have the most strongly peaked power-law density profiles.

Key words. stars: formation – stars: circumstellar matter – ISM: clouds – ISM: dust, extinction

1. Introduction

Stars are created from dense molecular clouds, and the morphology and density structure of the natal surroundings has a strong influence on the evolution and properties of the emerging protostars. For these reasons, much effort has been spent observing and analysing star-forming clouds in an attempt to understand what their structure may tell us about the star-formation process. Observations of star-forming material generally reveal low-mass cores to have power-law density structures consistent with gravity-driven infall and accretion, but similar insights towards high-mass stars have proved particularly difficult to obtain. Testing whether high-mass protostars have cloud structures similar to low-mass protostars has become a critical test in determining whether the paradigm of infall-driven low-mass star formation scales to the creation of the highest mass stars.

A particular threat to infall-driven formation mechanisms towards the higher mass regime has been the radiative feedback problem, whereby the luminosity of the growing protostar halts and eventually reverses the flow of infalling material. However, the recent work of McKee & Tan (2003) has emphasised the significant role that turbulence and density structure could play in countering increasing radiation pressure.

McKee & Tan showed that turbulence within a natal cloud of power-law density structure could force the highest accretion rates at the latest stages of evolution, when the protostellar luminosity is at its strongest, thereby allowing a high-mass protostar to continue to accrete material. Therefore, there are two focal points in testing this theory: measuring the turbulence of high-mass star-forming cores, and examining whether they are compatible with the power-law density structures that characterise infalling cores.

1.1. The structure of infalling cores

Observations of star-forming clouds have been most frequently compared to the Shu et al. (1987) framework which describes how the density structure of a core evolves as it collapses to form a star. As ambipolar diffusion causes the magnetic field supporting a core to dissipate, material falls inwards and the core begins to resemble an isothermal sphere of density profile $\rho \propto r^{-2}$. With density increasing fastest in the core centre, it is here in the core that self-gravity first overwhelms the supporting forces, and the cloud begins to collapse from the inside out. Shu (1977) proposed that an expansion wave propagates through the cloud: ahead of the wave, the envelope maintains an isothermal density structure ($\rho \propto r^{-2}$), while behind

the wave the density profile eventually flattens to $\rho \propto r^{-1.5}$ as material approaches free-fall closer to the core centre.

From an observer's standpoint, Shu's theory predicts we should detect cores with density structures of an inverse power-law form, with $\rho \propto r^{-\alpha}$ and α lying somewhere between 1.5–2.0. Although a more complete theory would also include perturbations introduced by magnetic fields (e.g. Galli 1993) and rotational flattening (e.g. Tereby et al. 1984), it is the simplicity of the Shu's predicted density structures that makes the framework so easily and frequently tested against observations.

While cores bearing low-mass stars have been frequently observed and can generally be characterised by power-law density structures consistent with Shu's predictions (e.g. Young et al. 2003; Hogerheijde & Sanderson 2000; Tafalla et al. 1998; Jørgensen et al. 2002; Shirley et al. 2000 and 2002), much less is known about the structure of high-mass cores. This is in part because the cores bearing young high-mass protostars are very scarce – there may be as few as 60 embedded early O-type stars in the Galaxy (Osorio et al. 1999). Additionally, high-mass stars soon clear and disrupt their natal surroundings, so evidence regarding the conditions and mechanisms critical to the formation of a high-mass star quickly becomes confused and obscured towards even moderately evolved high-mass protostars.

Those cores bearing young high-mass stars which have been observed and modelled display a range of density profiles. For example, high-mass stars associated with ultra-compact HII (UCHII) regions have been successfully modelled as protostars embedded in small, dense dust shells of constant density ($\alpha = 0$: Wolfire & Churchwell 1994), as stars within envelopes with isothermal profiles ($\alpha = 2$: Garay & Rodriguez 1990), and the recent modelling by Hatchell & van der Tak (2003) who found power-law density gradients of $1.25 < \alpha < 2.25$ towards a sample of UCHII/hot core sources. Whether these results reflect a highly diverse nature of UCHII-class sources, or whether such diversity arises from models using different numbers and qualities of observational constraint is not fully clear. However, a high-mass protostar luminous enough to drive a UCHII region could easily have disrupted its surroundings, so to remove uncertainty about the early evolutionary stages we must observe high-mass protostars *before* they have formed a UCHII region.

1.2. A new sample of candidate high-mass protostars

The lack of young high-mass protostars to study led Sridharan et al. (2002; SBSMW hereafter) to compile a new sample of candidate high-mass protostellar objects (HMPOs). SBSMW identified luminous objects similar in infrared colour to UCHII regions but without any associated free-free emission. These characteristics are thought to describe the potential precursors of UCHII regions: bright high-mass protostars that are young enough not to have significantly disrupted or ionised their surroundings. To summarise the specific constraints used to identify the sample (described in detail in Sridharan et al. 2002), bright IRAS point-sources ($S_{60} > 90$ Jy and $S_{100} > 500$ Jy) with infrared colours similar to known UCHII regions

(i.e. their colours conform to the Wood & Churchwell (1989) and Ramesh & Sridharan (1997) UCHII colour criteria) were selected by association with large amounts of dense molecular gas (via associated CS(2–1) emission) and their absence from Galaxy-wide 5 GHz continuum surveys. The 69 objects matching these criteria are potentially among the most deeply embedded, pre-UCHII, high-mass protostars in our Galaxy, a status supported by dust continuum observations (Beuther et al. 2002a, B2002a hereinafter; Williams et al. 2004), molecular line observations (SBSMW; B2002a), maser observations (SBSMW; Beuther et al. 2002b) and molecular outflow observations (Beuther et al. 2002c).

We recently observed the 850 μ m and 450 μ m continuum emission towards this sample using SCUBA (a bolometer array on the JCMT; Holland et al. 1999), the results of which are presented in the companion to this paper: Williams et al. 2004 (WFS hereinafter). In this paper we continue our analysis of the submillimetre (submm) emission by modelling the submm detections with DUSTY, a one-dimensional (1-D) radiative transfer code (Izević et al. 1999). In Sect. 2 we discuss the sources which we model, describing the model parameters in Sect. 3.1. DUSTY's output provides two points of comparison: a predicted spectral energy distribution (SED) for the modelled source, and a spatial emission profile. The techniques used to compare observed data and models are given in Sects. 3.2 and 3.3, giving a brief example of the analysis technique and its typical output in Sect. 3.4 before we present the complete set of best fits in Sect. 4. After a discussion of the implications of the best-fit parameters and a comparison to other models of young stars (Sect. 5), we conclude in Sect. 6 with a brief summary of our findings.

2. The sample

Our JCMT observations were directed towards bright IRAS point sources, each seen as a single, isolated detection between 12–100 microns, yet these targets were often resolved as multiple clumps in higher resolution 450 μ m, 850 μ m (Williams et al. 2004), and 1.2 mm continuum observations (B2002a). To remove the uncertainties and complexities multiple sources add to the modelling (such as apportioning the IRAS flux between the multiple submm sources), we primarily restricted our modelling to a subset of objects containing only a single submm source within the $\sim 120''$ SCUBA field of view. The 39 IRAS sources satisfying this criteria are listed in Table 1. As our spatial emission analysis technique allows us to attempt to model sources with companions, albeit with less certainty, we have also modelled a subset of five sources with companions. These sources are listed in the second section of Table 1.

3. Radiative transfer models

To predict the appearance of a deeply embedded protostar it is necessary to model the absorption, scattering, and reddening effects of the surrounding envelope, and for this we used the 1-D radiative transfer code DUSTY (Izević et al. 1999). We created hundreds of unique models by varying input parameters, and by comparing the models to the observed

Table 1. The positions, WFS and IRAS identifiers of the sources modelled in this paper. Sources in the first section of the table contain just one IRAS, JCMT, and IRAM detection within an IRAM field of view, while sources in the second section have multiple submillimetre components associated with the single IRAS detection.

WFS	IRAS	Position	
		RA(J2000)	Dec(J2000)
6	05553+1631	05 58 13.9	+16 32 00
13	18102–1800	18 13 12.2	–17 59 35
14	18151–1208	18 17 57.1	–12 07 22
15	18159–1550	18 18 47.6	–15 48 54
16	18182–1433	18 21 07.9	–14 31 53
18	18247–1147	18 27 31.1	–11 45 56
19	18264–1152	18 29 14.3	–11 50 26
28	18310–0825	18 33 47.2	–08 23 25
29	18337–0743	18 36 29.0	–07 40 33
30	18345–0641	18 37 16.8	–06 38 32
34	18372–0541	18 39 56.0	–05 38 49
35	18385–0512	18 41 12.0	–05 09 07
36	18426–0204	18 45 12.8	–02 01 12
37	18431–0312	18 45 46.9	–03 09 24
42	18440–0148	18 46 36.3	–01 45 23
43	18445–0222	18 47 10.8	–02 19 06
50	18454–0136	18 48 03.7	–01 33 23
54	18470–0044	18 49 36.7	–00 41 05
59	18521+0134	18 54 40.8	+01 38 01
61	18530+0215	18 55 34.2	+02 19 08
64	18553+0414	18 57 53.0	+04 18 06
65	18566+0408	18 59 09.9	+04 12 14
66	19012+0536	19 03 45.1	+05 40 40
67	19035+0641	19 06 01.1	+06 46 35
72	19217+1651	19 23 58.8	+16 57 36
73	19220+1432	19 24 19.7	+14 38 03
74	19266+1745	19 28 54.0	+17 51 56
77	19403+2258	19 42 27.2	+23 05 12
80	19411+2306	19 43 18.1	+23 13 59
85	20051+3435	20 07 03.8	+34 44 35
90	20126+4104	20 14 26.0	+41 13 31
93	20216+4107	20 23 23.8	+41 17 40
94	20293+3952	20 31 10.7	+40 03 10
95	20319+3958	20 33 49.4	+40 08 45
101	22134+5834	22 15 09.1	+58 49 09
108	23033+5951	23 05 25.2	+60 08 11
109	23139+5939	23 16 09.3	+59 55 23
110	23151+5912	23 17 21.1	+59 28 49
Fields with multiple detections			
20,21	18272–1217	18 30 02.7	–12 15 27
25	18306–0835	18 33 21.8	–08 33 39
55,56	18472–0022	18 49 50.7	–00 19 09
78,79	19410+2336	19 43 11.6	+23 44 06
106,107	22570+5912	22 59 06.5	+59 28 28

emission we identified which parameters best describe the observed cloud structure. The DUSTY code has a history of application to star-forming regions, and has been successfully used to model a number of other embedded protostars, from low-mass protostars (Jørgensen et al. 2002) to young high-mass stars associated with UCHII regions (Hatchell et al. 2000).

3.1. Input parameters

We based many input parameters on the models of Hatchell et al. (2000), who used DUSTY to model the dust emission seen towards young UCHII-class high-mass stars of comparable luminosity to our sample. Although the luminosity range of our sample spans many spectral types, changing the input luminosity of the model has little effect on the model output (Hatchell et al. 2000; Jørgensen et al. 2002), so we mirrored Hatchell et al.’s (2000) choice of illuminating source by modelling an embedded O6 star, which has a spectral profile equal to a blackbody at a temperature of 43 000 K.

Around the illuminating protostar we modelled a dense dusty shell, which we call the envelope. DUSTY is a 1-D code, so the enclosing envelope is considered spherically symmetric and all distance terms are given by the radial offset r from the central star. It is assumed that a dust-free cavity exists around the protostar, stretching from $r = 0$ to $r = R_{\text{inner}}$ (the inner radius of the dust shell) while the envelope extends from R_{inner} to R_{outer} (the outer boundary of the dust envelope). These quantities are defined in terms of T_{inner} , the radiation temperature at R_{inner} , and Y , the shell thickness measured as $R_{\text{outer}}/R_{\text{inner}}$. For example, the input parameters $Y = 50$ and $T_{\text{inner}} = 300$ K describe an envelope existing between 10^{17} cm and $\sim 5 \times 10^{18}$ cm from the protostar, extending around $190''$ in diameter across the plane of the sky at a typical sample projected distance of 4 kpc. We modelled inner temperatures of $300 \text{ K} \leq T_{\text{inner}} \leq 1700 \text{ K}$ and shell thicknesses of $1 \leq Y \leq 12\,000$, the only constraint being that the temperature at R_{outer} must be ≥ 10 K to avoid unrealistically low boundary temperatures and overly extended envelopes.

The density of each model clump was defined by its optical depth at $100 \mu\text{m}$ (τ_{100}); we modelled optically thin shells of $\tau_{100} = 0.1$ through to extremely thick cores with $\tau_{100} = 20$. For continuity with the Churchwell et al. (1990) and Hatchell et al. (2000) studies, we assume the envelopes are homogeneous in composition, with a standard Draine & Lee (1984) dust grain size distribution and silicon-to-graphite ratio equal to half that of the interstellar medium (Mathis et al. 1977).

The short history of modelling embedded high-mass stars has shown that they can be described by power-law density structures of the form $\rho(r) \propto r^{-\alpha}$, ranging from constant density shells ($\alpha = 0$; Churchwell et al. 1990), to shallow fall-offs ($\alpha \sim 1$), to more centrally peaked envelopes ($\alpha \sim 2$). In light of such a wide range of power-law density indices, we have concentrated in this study on the discrete density indices $\alpha = 0.0, 0.5, 1.0, 1.5, 2.0$ and 2.5 , from which we hope to learn which density structures may be eliminated and where to target more detailed models in the future.

Table 2. Parameters used for models with inner dust boundary temperatures of $T_{\text{inner}} = 300$ K.

Y	τ_{100}																		
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.5	1.6	2	2.5	3	3.2	3.5	4	5
10	X	X	X	X	X	X	X	X	X	X	X	-	X	X	X	-	X	X	X
15	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
20	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
25	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
30	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
35	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
40	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
45	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
50	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
55	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
60	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
65	-	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
70	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
100	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
200	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
400	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
600	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
800	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
1000	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
1300	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
1600	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
2000	X	X	X	X	X	X	X	X	X	X	X	-	X	-	X	-	-	X	-
3200	X	X	-	X	-	-	-	X	-	-	-	X	-	-	-	X	-	-	X
6400	X	X	-	X	-	-	-	X	-	-	-	X	-	-	-	X	-	-	X

Table 3. Parameters for models with inner dust boundary temperatures of 500 K, 800 K, 1200 K, and 1700 K. An index of 1 means only this optical depth was input for $T_{\text{inner}} = 500$ K, 800 K, and 1200 K models, while an index of 2 means this optical depth was only used for $T_{\text{inner}} = 500$ K and 800 K models.

Y	τ_{100}					
	0.1	0.2	0.4	0.8	1.6	3.2
50	X	X	X	X	X	X
100	X	X	X	X	X	X
200	X	X	X	X	X	X
400	X	X	X	X	X	X
800	X	X	X	X	X	X
1600	X	X	X	X	X	X
3200	X	X	X	X	X	X
6400	X	X	X	X	X	1
12000	-	-	-	2	2	2

The density distribution, optical depth and dust shell thicknesses considered in this study are listed in Table 2 and Table 3.

Previous modelling of deeply embedded young stars has shown that the SED and the spatial distribution of the

emission are primarily sensitive to different model parameters. In particular the spatial distribution of the optically thin submm emission modelled here is relatively insensitive to the τ_{100} (e.g. Jørgensen et al. 2002). As such it is possible to a reasonable degree of accuracy to decouple the modelling of the SED and the maps of a source. We do this by modelling the SED and then using the best fit value of τ_{100} in fitting the spatial distribution of the emission.

3.2. Model analysis: SED

We quantified the SED goodness of fit as the sum of χ^2 measured between model flux predictions (S^{mod}) and the observed constraints (S^{obs} , comprising 12, 25, 60, and 100 μm IRAS limits, our 450 μm and 850 μm limits, and the B2002a 1.2 mm constraints) weighted by the optical depth (τ_λ) at the constraint wavelength (λ), so that

$$\chi_{\text{SED}}^2 = \sum \frac{(\log S_\lambda^{\text{model}} - \log S_\lambda^{\text{obs}})^2}{\tau_\lambda}, \quad (1)$$

having first scaled the flux-normalised model to the observed data by minimising χ_{SED}^2 . The discontinuous model

Fig. 1. A comparison of the model SED (solid line) to the observed flux constraints (symbols) for WFS 42 (IRAS 18440-0148). All SED plots within Figs. 5 and 7 maintain the x and y axis limits, with wavelength ranging from $1\text{--}10^4\ \mu\text{m}$ (x axis) and flux density spanning $0.1\text{--}10^5\ \text{Jy}$ (y axis).

spectra were interpolated to provide data at the observed wavelengths wherever necessary; the model SEDs were smooth and well constrained, and we estimate any uncertainties introduced through interpolation to be negligible.

SBSMW suggested the positional offsets of submm clumps and their associated IR detections could be explained if the emission at IR and submm wavelengths originates from distinct sources. This may be true, as the opacity of our models when scaled to match our $450/850\ \mu\text{m}$ observations suggests that the majority of clumps are optically thick below $\sim 75\ \mu\text{m}$, letting very few IR photons escape these cold, submm-bright envelopes. On the other hand, asymmetric envelope morphologies and excavation by outflows could provide a low-opacity escape route for short-wavelength photons, but these are not modelled by a 1-D code. For these reasons, we introduced the $1/\tau_\lambda$ weighting to prevent model SEDs being scaled and judged against short-wavelength flux potentially originating from other (perhaps less obscured) objects or by photons escaping through low-opacity cavities. We chose to weight by $1/\tau_\lambda$ as τ_λ gives some measure of whether photons are received from their point of origin, not via reprocessing material or deflection from another source, plus τ_λ is continuous and easily identifiable at all wavelengths considered, for having set the dust composition, τ_λ is calculated by DUSTY. With greatly reduced opacity at longer wavelengths, this ensures we preferentially scale the models to match the data in the optically thin submm regime, where we also try to fit the spatial emission data. With the $1/\tau_\lambda$ weighting, while valid “cold-component” models (e.g. Fig. 1) could be considered good fits despite their lack of short-wavelength emission, we emphasise that a model matching all observed points is still considered the best fit by this procedure.

3.3. Model analysis: Spatial emission

Having quantified the goodness of SED fit, we proceeded to evaluate the spatial emission profile of each model. As the spatial emission models are flux normalised, they become essentially independent of τ_{100} , so by considering only those models

whose τ_{100} gives the optimum SED fit we effectively eliminated one degree of freedom from the emission profile comparison and saved considerable computational time. Additionally, we only compare the model profiles at $850\ \mu\text{m}$, as poor signal-to-noise in our JCMT $450\ \mu\text{m}$ maps prevents any useful examination of emission lying outside a beamwidth in size (where the fit is most tightly constrained), and also because the JCMT beam is much simpler at $850\ \mu\text{m}$, thus we avoid the significantly increased $450\ \mu\text{m}$ error lobes that would add uncertainty to our analysis.

To compare the 1-D models and 2-D observations, we created 2-D simulated jiggle-maps from the models, using the following steps to reproduce any asymmetries or artefacts introduced by the observing procedure:

1. Form a 2-D map from DUSTY’s 1-D spatial emission profile, assuming spherical symmetry, projecting the source to the appropriate kinematic distance (the near kinematic distance if distance unresolved), and rebinning the data into $3''$ pixels.
2. Convolve the 2-D model with the JCMT point source function (PSF) extracted from the map of Uranus observed closest in time to the source observation, thus simulating the JCMT response.
3. Our observations used a $120''$ chop to measure the level of background emission, so reproduce any self-chopping artefacts by subtracting a copy of the convolved model as observed from a $120''$ offset in azimuth. This step becomes increasingly important for model envelopes that extend outside the JCMT’s $\sim 2'$ field of view.
4. Scale the model so that the peak levels of the observed map and simulated map are equal.

All operations were performed in the azimuth-elevation coordinate frame to keep asymmetric PSF and chop artefacts consistently orientated.

Having produced a final simulated map, we then sampled 1-D cross-sections of the model observation and compared them to 1-D cross-sections of the observed data. Cross-sections were measured both by forming the azimuthal average and by measuring cuts of emission passing through the emission peak (“radial slices”). Example cross-sections measured for a simulated map and observed map, alongside the assumed PSF, can be found in Fig. 2, which also provides a magnified example of the diagram type to be found later in Fig. 7. Regardless of how cross-sections were sampled, the goodness of each profile fit was measured by χ^2 between model cross-section and observed cross-section, where

$$\chi_{\text{PROF}}^2 = \sum_{r=0}^{r=R} (\log S_r^{\text{model}} - \log S_r^{\text{obs}})^2, \quad (2)$$

and r spans the radial distance from the peak of emission ($r = 0$) to the point at which background noise is reached ($r = R$).

For asymmetric sources it is doubtful that azimuthal average fits produce physically meaningful results, so for asymmetric sources we used radial slices to fit the models and to explore how source structure differs depending on orientation. Bad data caused by noisy bolometers or chopping onto other

Fig. 2. A comparison of the observed 850 μm spatial emission profile and an 850 μm model emission profile for WFS 65 (IRAS 18566+0408). The observed data is plotted by circular symbols linked by a dashed line, while the model emission profile is plotted by a solid line and the profile of Uranus (representative of the telescope PSF) by a faint dotted line. The x -axis measures the angular extent of the envelope in arcseconds, while the y -axis measures flux in units of Jy per 14.4'' beam.

source emission was also excluded by limiting the range of position angles from which radial slices were sampled. By pooling and combining the remaining orientations that sampled good data, we formed in effect a corrected azimuthal average. We tested the similarity of the true azimuthal average and a “pseudo azimuthal average” measured by pooling radial slice fits by sampling maps of highly symmetric sources with no detectable chopping artefacts, and found the results of azimuthal-average and pooled radial slices to be highly similar: of the 300+ models considered, the best-fit populations were almost identical.

Once all position angles were sampled and fitted, the best fit was then identified:

- If the source appeared symmetric and radial slices measured across different orientations gave the same results, the best azimuthal average model was considered to be the best spatial emission fit.
- If a single model could not fit all emission features, but radial slices show these features could be fit independently, we quote the best fits in terms of the best radial slices with their applicable range of position angle.

Finally, we combined the results of the SED and profile tests by a simple cumulative rank (or tally) method. Defining the rank of a model in the SED test by R_{SED} and in the profile test by R_{PROF} , the best model was identified as the model with minimum $R_{\text{SED}} + R_{\text{PROF}}$. We choose to use the cumulative rank instead of some combination of χ^2_{SED} and χ^2_{PROF} as it is not clear how to combine χ^2_{SED} and χ^2_{PROF} as the observations contributing to the two fits are not independent while the SED and profiles constrain different model parameters (Jørgensen et al. 2002). Furthermore for different sources the values of χ^2 have different numerical scales, so χ^2 only has meaning in an ordinal comparison with results from the same test for a given source. We therefore consider it better to use a simple non-parametric quantity, the overall rank, to identify the best overall fit.

Fig. 3. The best SED and profile fits are identified separately by minimum χ^2 (upper plots; greyscales contour χ^2 at 5%, 10%, 15%, 20%, 25%, 30%, 40%, 60%, and 80% of maximum χ^2 , from light grey to dark grey). Using the χ^2 results, the models are then mapped by rank (middle plots; greyscales contour the population in steps of 10% from dark grey (best fits) to light grey (worst fits). The best ten fits also have their rank printed by a number at the appropriate location in parameter space. These results are then combined, giving the best overall fit as the model with highest cumulative rank (tally) (bottom plot).

An example of how models are distributed in parameter space by χ^2 and rank, and how these results are combined to identify the best overall fit is shown in Fig. 3.

3.4. Analysis example

To illustrate our use of radial slices, we present a more detailed examination of WFS 65 (IRAS 18566+0408), a source characterised by extended emission with an almost 2:1 major-axis to minor-axis ratio (Fig. 4). Figure 5 presents the best 10 model fits to the azimuthally averaged emission, where we see that despite the asymmetric nature of the 850 μm emission, good fits can be found to the unrepresentative azimuthally averaged emission. The parameters of these 10 best-fit models are given in Table 4, and the location of the best fits in Y , T_{inner} , and

Fig. 4. A map of the 850 μm emission seen towards WFS 65 (IRAS 18566+0408). The triangular symbol displays the location of MSX source in the field of view. Contours trace the level of 850 μm emission (S_{850}) in steps of $\Delta S_{850} = 0.50 \text{ Jy beam}^{-1}$ from $S_{850} = 0.50 \text{ Jy beam}^{-1}$, while the axes give right ascension and declination in J2000 coordinates.

α parameter space is illustrated in Fig. 6. We see the best azimuthal average fits are located together in a similar area of parameter space, with 6 of the best 9 fits having $T = 300 \text{ K}$ and dust shell sizes centred around $Y = 100$.

However, by measuring and modelling the major and minor axes independently, we find different best fits for the perpendicular faces. A series of plots comparing the observed emission to the best azimuthal average, minor axis and major axis model fits can be found in Fig. 7. Here we see that the minor axis emission falls more steeply with $\alpha = 1.5$ compared to the $\alpha = 1.0$ density gradient that fits the major axis, suggestive of a clump more cylindrical than spherical in shape. This figure emphasizes that while reasonable fits to the azimuthal average may be obtained, they are not always representative of the source structure. Many of the young high-mass stars in our sample are embedded in envelopes that appear clumpy, extended or filamentary in appearance, and while we gain greater signal-to-noise by averaging to an azimuthal average cross-section, it is only by sampling individual features that we can fully describe the observed emission.

4. Results

We successfully fit power-law density profiles to 36 of the 39 companionless IRAS fields modelled. The parameters of the best-fit models are listed in Table 5. The intensity profiles of the best-fit models are presented in Fig. 8. We do not plot the SED fits as they show little variation from the “cold component” SEDs of Sridharan et al. (2002). While there are many areas of parameter space which could fit the source SEDs, the requirement of simultaneously matching the observed spatial emission provides a stringent constraint on the models.

Fig. 5. Profile fits and SEDs for the best ten models for WFS 65 (IRAS 18566+0408), where the spatial emission profiles consider the azimuthally averaged emission. Plots are ordered by quality of fit, beginning at the top with the best model and finishing with the 10th best model at the bottom. The SED and profile of each model are placed in the left-hand and right-hand columns respectively.

Table 4. A table listing the parameters of the best 10 models for fits to the azimuthally averaged emission seen towards WFS 65 (IRAS 18566+0408).

Tally position	α	Y	Dust shell radius		Boundary temp.		τ_{100}	$\log L/L_{\odot}$	Spectral type
			inner	outer	inner	outer			
			$\times 10^{15}$ cm	$\times 10^{17}$ cm	K	K			
1	1.5	400	18.4	7.4	500	12	3.2	4.92	O7.5
2	1.5	100	50.7	5.1	300	13	3.0	4.93	O7.5
3	2.0	100	58.2	5.8	300	13	5.0	5.01	O7
4	1.5	200	45.8	9.2	300	10	2.0	4.86	O8
5	1.5	1600	6.9	11.1	800	11	3.2	4.95	O7.5
6	1.0	800	6.2	5.0	800	13	1.6	4.89	O8
7	1.5	800	18.5	14.8	500	10	1.6	4.94	O7.5
8	1.0	100	46.0	4.6	300	13	1.5	4.87	O8
9	1.0	70	49.4	3.5	300	14	2.0	4.93	O7.5
10	1.5	70	54.5	3.8	300	14	3.0	4.99	O7.5

Fig. 6. A series of plots displaying Y and α parameter space for WFS 65 (IRAS 18566+0408). The left-hand column displays the best-fit population for azimuthal-average fits, while the centre and right-hand columns display fits for major and minor axes respectively. Rows are arranged by T_{inner} , with $T_{\text{inner}} = 300$ K, 500 K and 800 K from top to bottom. Models were also evaluated at $T_{\text{inner}} = 1200$ K and $T_{\text{inner}} = 1700$ K, but these temperatures provide no fits of any significance and are omitted from this figure. Greyscales map the model population in steps of 10% from dark grey (best fits) to light grey (worst fits).

Fig. 7. The best SED and spatial profile fits for WFS 65 (IRAS 18566+0408), compared to the emission from which they were sampled. The best-fit models for three different orientations are compared: the major axis, the minor axis and the azimuthally averaged emission. Models are grouped into rows by which orientation they fit best. For each row, the left column presents the SED for the best-fit model, followed by profile fits which compare the model spatial emission to the real emission observed in each orientation. The dashed, solid and faint dotted lines plot the observed, model, and PSF emission cross-sections, as described in Fig. 2. The parameters of each best-fit model can be found in Table 5.

Even so, some of the very best profile fits are excellent (e.g. Fit #9, #15, #18, #35).

As discussed for WFS 65, a number of sources show significantly different best fits depending on the direction in which the source emission is sampled. Whether these differences reflect the presence of multiple unresolved clumps or intrinsically non-spherical density distributions will require higher angular resolution observations and more detailed modelling, but these results do highlight that fitting solely to azimuthally-averaged emission may give erroneous physical parameters.

Using our radial slice technique we could also successfully fit power-law density profiles to four IRAS fields containing

multiple objects. The best-fit parameters of these multiple-source models are listed in the second half of Table 5. We see that the density gradient of multiple-component envelopes are generally similar to those of solitary cores. We note, however, that the uncertainties of these multiple component fits are increased, as avoiding emission shared between the source and its neighbouring components often leaves just a small area of emission from which to sample. In addition, a mosaic of jiggle-maps is often needed to complete the view of the multiple system, but these constituent maps cannot be co-added in the azimuth-elevation frame required for chopping compensation. This leaves single jiggle-maps and a reduced field-of-view with

Table 5. continued.

Fit number	WFS	IRAS field	Position Angle		α	Y	Dust shell radius		Boundary temp.		T_{bol} K	τ_{100}	Log $L/L_{\odot}$	Sp. type	M/L $M_{\odot}/L_{\odot}$
			Start Deg	End Deg			inner $\times 10^{15}$ cm	outer $\times 10^{17}$ cm	inner K	outer K					
34	77	19403+2258			1.0	800	6.1	49.2	500	11	180	0.4	4.0	B1	5.75
35	80	19411+2306			1.0	200	11.8	23.7	300	10	42	1.0	3.7	B2	29.97
36	85	20051+3435			1.0	200	16.8	14.3	300	11	45	0.9	3.3	B3	19.22
37	"	"	150	300	1.5	200	17.3	15.7	300	10	35	3.0	3.3	B3	17.11
38	90	20126+4104			1.5	70	17.8	14.1	300	14	32	5.0	4.1	B0.5	7.51
39	"	"	330	60	2.0	100	18.3	21.5	300	13	38	5.0	4.1	B0.5	6.94
40	93	20216+4107			1.0	70	16.9	6.8	300	14	35	2.0	3.5	B2	11.66
41	94	20293+3952			1.0	400	3.4	13.8	500	11	37	1.6	3.5	B2	20.92
42	"	"	340	20	1.5	200	10.1	20.1	300	10	35	3.0	3.5	B2	19.54
43	95	20319+3958			1.5	50	17.4	5.8	300	16	38	3.0	3.6	B2	2.28
44	"	"	70	270	1.5	800	6.3	29.4	500	10	52	1.6	3.5	B2	2.88
45	101	22134+5834			1.0	400	6.1	21.8	500	11	37	1.6	3.9	B1	11.54
46	"	"	major axis		1.0	200	16.8	29.1	300	11	45	0.9	3.9	B1	12.11
47	"	"	minor axis		1.5	200	17.3	31.8	300	10	35	3.0	3.9	B1	10.78
48	108	23033+5951			1.5	400	6.4	39.6	500	12	41	3.2	4.4	B0.5	9.93
49	"	"	200	250	1.0	1600	2.2	43.6	800	10	39	1.6	4.2	B0.5	15.85
50	109	23139+5939			1.5	1600	2.3	67.7	800	11	48	3.2	4.5	B0	13.89
51	110	23151+5912			1.5	400	6.4	61.6	500	12	41	3.2	4.8	O8.5	4.95
52	"	"	0	160	1.5	200	17.0	80.6	300	11	44	1.5	4.7	O8.5	5.09
53	"	"	220	220	2.0	100	18.3	48.7	300	13	38	5.0	4.8	O8	4.04
Sources with close companions															
54	25	18306-0835			1.5	200	26.9	53.9	300	10	35	3.0	4.4	B0.5	21.28
55	55	18472-0022			1.0	200	15.3	30.7	300	10	42	1.0	3.9	B1	18.11
56	56	"			1.0	200	15.3	30.7	300	10	42	1.0	3.9	B1	3.36
57	79	19410+2336			1.5	50	24.1	12.0	300	16	33	5.0	4.3	B0.5	12.80
58	78	"			1.5	200	18.9	37.9	300	10	35	3.0	4.1	B0.5	2.33
59	107	22570+5912			0.5	70	35.0	24.5	300	14	33	1.5	4.6	O9.5	8.00
60	106	"			1.5	100	39.0	39.0	300	12	31	5.0	4.7	O9	2.67

Fig. 8. Profiles of the best-fit models. Profiles are labelled by fit number as listed in Table 5 and WFS identifier. Observed data are plotted by circular symbols joined by a dashed line, model profiles drawn with a solid line, and the profile of Uranus (representative of the telescope PSF) traced by a faint dotted line. For each panel the x axis measures the radial extent of the envelope in arcseconds while the y axis measures flux.

which to model the detections. Due to these uncertainties, we only further analyse the properties and quote the mean parameters of sources without companions.

4.1. Density structure

A histogram of the α distribution for our models is presented in Fig. 9. Considering all 36 successfully fitted sources, we find a mean density power law index of $\bar{\alpha} = 1.3 \pm 0.4$, where the quoted uncertainty is the standard deviation of the sample. This is significantly flatter than $\bar{\alpha} = 2.0$ typically found for low-mass objects, but is similar (within the uncertainties) to other objects of similar luminosity (Hatchell et al. 2000; Mueller et al. 2002; Hatchell & van der Tak 2003; van der Tak et al. 2000). The mean index lies in between that of a logotropic density profile ($\alpha = 1$) and Shu’s infall profile ($\alpha = 1.5$ – 2.0), so we cannot eliminate either profile regime from our sample of pre-UCHII sources.

The structure of our candidate HMPOs have been independently assessed by B2002a, who fit power-laws directly to

the 1.2 mm continuum emission and derived density structures from the empirical results. Rebinning B2002a data into bins of width $\Delta\alpha = 0.5$ gives a 1.2 mm mean power-law index of $\bar{\alpha} = 1.6 \pm 0.4$. Excluding sources not modelled in our study from the B2002a data does not change this index, nor the uncertainty, and both results are consistent within these uncertainties to our analysis of the $850 \mu\text{m}$ emission.

To perform a deeper comparison of our α distribution to that of other studies, we rebinned the data of other studies into bins of width $\Delta\alpha = 0.5$, equal to the step-size used by our models. The rebinned α distributions can be seen and compared in Fig. 10. Applying the Kolmogorov-Smirnov two-sample test reveals that while the mean index of our survey may be comparable within the uncertainty limits to the Mueller et al. (2002) study, the distributions are quite different. The null hypothesis that our α distribution is similar to the Mueller et al. distribution is rejected at a $>99\%$ confidence level. While we find suggestive evidence of differences between our α distribution and that of the SBSMW sample as a whole ($\sim 95\%$ confidence level), eliminating SBSMW sources not modelled in this

Fig. 9. A histogram of the best-fit power-law indices (α) for sources modelled in this study, plotted with a bin size of $\Delta\alpha = 0.5$.

survey from the SBSMW distribution lessens this difference to a $\sim 90\%$ confidence level: statistically, weak evidence for a difference. Interestingly, the Kolmogorov-Smirnov test reveals little difference between the α distribution of any high-mass sample and that of the Jørgensen et al. (2002) sample of low-mass protostars.

The difference between our results and that of SBSMW may arise from differences in fitting technique. The B2002a analysis of this sample concluded that the density profile could not be fitted by envelopes of a single power-law form alone: instead, a break-point was introduced, introducing an additional power-law fit to emission lying outside $32''$. However, our study finds no requirement for an additional breakpoint as the quality of fit using a single power-law is usually of a high standard; unfortunately it becomes difficult to compare double power-law profiles to our single power-law results. (For reference, we excluded the post-breakpoint regions when calculating $\bar{\alpha}$ for the SBSMW study). The reason why a breakpoint is unnecessary is not immediately clear. It is most likely because we include a more complete simulation of the chopping, but differences could also occur because the different methods used to determine the density gradient. B2002a calculated the density gradient directly from measurements of the observed intensity gradient assuming a simple approximation for the temperature gradient, whereas in our study, given the density profile being modelled, the temperature gradient and emission are calculated self-consistently.

4.2. Optical depth

A histogram of the best-fit τ_{100} values is presented in Fig. 11, which shows the HMPOs are optically thick at $100 \mu\text{m}$. As a result, virtually all photons are absorbed at IR wavelengths and the majority of models have an SED similar in shape to a SBSMW “cold-component” model. The mean optical depth of our sample is $\bar{\tau}_{100} = 2.7 \pm 0.3$, where the uncertainty is the standard error of the mean. In relative terms, this opacity lies between the thick cores ($\tau_{100} = 10$) embedded in thin extended envelopes ($\tau_{100} \sim 0.5$) proposed by Hatchell et al. (2000). The quality of the spatial emission fits for our models suggests a

separate optically-thick component is not required for most of our sample.

Our results also differ from Churchwell et al. (1990), whose optically thin ($\tau_{100} < 1$), constant density ($\alpha = 0$) envelope models matched the IR flux constraints towards their UCHII-class sample. Our models show that optically thin shells cannot recreate the observed submm luminosity. Also, the Churchwell et al. (1990) models were found without testing against spatial emission profiles, where our models show that thin, constant density models are a poor match to the observed emission. These differences may be due to evolution of the density structure and optical depth, for Churchwell et al. (1990) and Hatchell et al. (2000) modelled more evolved sources already associated with UCHII regions and hot cores.

4.3. Luminosity

We calculated the bolometric luminosity of each model by integrating the SED over all wavelengths, finding a mean luminosity of $(\log L/L_{\odot}) = 4.2 \pm 0.1$, equivalent to a B0.5 spectral type, where the uncertainty represents the standard error of the mean. This mean luminosity would fall slightly short of the true mean if the IR constraints should also be satisfied by the models. However, SBSMW showed that the addition of a hot dust component usually adds no more than 5% to the luminosity, making minimal difference to the spectral type. Figure 12 presents a histogram of the luminosities implied by our best-fit models.

5. Discussion

5.1. Evolutionary trends

Beuther et al. (2002a) examined whether the density structure evolves as a young star matures by dividing the sample of HMPOs into three groups, based on their association with signposts of high-mass star formation. These groups consist of sources strong in hot core tracers CH_3OH and/or CH_3CN with no resolved continuum radio emission (Group 1), radio continuum resolved sources (Group 2), and CH_3OH and CH_3CN non-detections with no resolved cm emission (Group 3). Arranging these groups into their expected evolutionary sequence, we have the youngest cores collected in Group 3, evolving through Group 1 before they reach the most evolved status in Group 2.

Sources with no other signposts of massive star-formation (Group 3) are small in number, and are characterised by a mean density index of $\bar{\alpha} = 1.3 \pm 0.1$. The cm unresolved sources in Group 1 become more peaked, with $\bar{\alpha} = 1.6 \pm 0.1$, whereas the cm-resolved sources in Group 2 are associated with more shallow envelopes of $\bar{\alpha} = 1.2 \pm 0.2$ (all uncertainties represent the standard deviation). The small number of sources in each group means we cannot perform meaningful Kolmogorov-Smirnov tests to discern whether the difference in distributions is statistically significant.

Fig. 10. Histograms of the density profile power-law index α for the current study (dark grey; plot **a**), the high-mass studies of Beuther et al. (2002a; light grey, plot **c**), Mueller et al. (2002; mid grey, plot **b**), and the low-mass study of Jørgensen (2002; clear bars, plot **d**), all rebinned into bins of width $\Delta\alpha = 0.5$.

Fig. 11. A histogram of the $100\ \mu\text{m}$ optical depths (τ_{100}) leading to the best SED fits for our study (dark grey bars) and for the Jørgensen et al. (2002; clear bars) study of low-mass protostars.

Fig. 12. A histogram of the best-fit model luminosities with bin width $\Delta(\log L/L_\odot) = 0.25$.

5.2. Cavity size

Churchwell et al. (1990) proposed that the large dust-free cavities (i.e. low values of T_{inner}) associated with their modelled sources were indicative of an additional force excavating a cavity around the star – perhaps radiation pressure acting on the dust, interaction with a stellar wind, or dust destruction in shocks. As such, T_{inner} represents the point of balance between dust excavating forces and countering infall motion. Churchwell (2002) further suggested that precursors of UCHII regions should have comparatively smaller inner cavities, as larger infall rates would push the inner boundary closer to the protostar. If this were true, we would expect the young sources in our sample to display higher T_{inner} than more evolved UCHII sources.

Our models with smaller dust-free cavities ($T_{\text{inner}} = 500\ \text{K}$, $800\ \text{K}$, $1200\ \text{K}$ and $1700\ \text{K}$) test this prediction. For a fixed shell thickness and density profile, we can move along the T_{inner} dimension; an example of how the fits change by moving along the T_{inner} axis can be found in Fig. 14. We found 10 sources were best fit with envelopes of $T_{\text{inner}} = 500\ \text{K}$, and 3 sources were best fit with envelopes of $T_{\text{inner}} = 800\ \text{K}$. The majority of the sample are more successfully modelled when $T_{\text{inner}} = 300\ \text{K}$ (e.g. Fig. 14), showing no change from

the best-fit T_{inner} of UCHII-class samples (Churchwell et al. 1990; Hatchell et al. 2000). However, we find no significant correlation between Beuther et al. 2002a evolutionary indicator and T_{inner} , so it is still not clear whether the forces supporting the envelope change in magnitude as the source evolves.

With a typical dust sublimation temperature of $\sim 1700\ \text{K}$, the dust grains towards our sources should be capable of surviving much closer to the illuminating protostar than a $T_{\text{inner}} = 300\ \text{K}$ boundary suggests, indicating that a strong excavating force must already be active in the early stages of a high-mass star's evolution. However, it is important to note that our sample lies between 1–10 kpc distant, so we cannot physically resolve the extent of any inner cavity; we can only derive T_{inner} and R_{inner} by fitting the SED and the spatial profile lying far beyond the inner boundary. Observations of high-resolution temperature tracers would be most useful in confirming these results.

5.3. Comparison to low-mass cores

We also compared our results to Jørgensen et al.'s (2002) models of low-mass Class 0/Class I protostellar cores. We compared against this particular low-mass study as the continuum emission towards these objects was modelled using DUSTY in

Fig. 13. A series of histograms plotting the progression of the density profile power-law index α . Histograms are arranged in the expected evolutionary sequence, beginning with sources with no CH₃OH and CH₃CN association or resolved cm emission (Group 3), continuing to sources strong in hot core tracer CH₃OH and/or CH₃CN but no resolved cm emission (Group 1) and resolved cm sources (Group 2). The modelled sources which could not be placed into one of these groups are shown in the rightmost panel (Remainder).

Fig. 14. A comparison of the observed and model spatial emission profiles for WFS 37 (IRAS 18431-0312), demonstrating how changes in T_{inner} affect the quality of fit and how good fits are a fine balance between all parameters. In this figure, the density profile and shell size are kept constant ($\alpha = 1.0$ and a thickness of 4×10^{18} cm) while T_{inner} changes. Although the $T_{\text{inner}} = 300$ K model has a good SED fit, the profile fit is poor. As the dust-free cavity shrinks, the fit becomes better, though as the shell begins to contain more hot dust an increase in optical depth is necessary to maintain a good SED fit in the submm regime (here using $\tau_{100} = 0.7$ for the $T_{\text{inner}} = 300$ K model to $\tau_{100} = 1.6$ for the $T_{\text{inner}} = 500$ K and $T_{\text{inner}} = 800$ K models).

a very similar fashion to this study, but using input parameters more suited to low-mass protostars: T_{inner} was fixed at 250 K for the low-mass models; α was allowed more freedom than the fixed $\Delta\alpha = 0.5$ increments of our analysis, while as they considered less luminous objects, a blackbody of temperature 5000 K was selected as the illuminating source. Revisiting

Fig. 15. A comparison of the dust envelope outer boundary (R_{outer} ; left-hand plot), and the shell size ratio (Y ; right-hand plot) and their relationship with the best-fit density profile power-law index (α). Models of low-mass sources (Jørgensen et al. 2002) are plotted by open circles, while the best high-mass models are plotted by filled rectangles.

Fig. 10, we see that the distribution of our high-mass sample is centred at lower values of α , an observation strengthened considering the low α tail of the Jørgensen et al. distribution mainly consists of pre-stellar cores, which our sample does not include. This difference may be indicative of the proposed additional non-thermal force in high-mass envelopes (Churchwell et al. 1990).

Although high-mass envelopes are smaller in relative terms than those surrounding low-mass protostars (Fig. 15a), in absolute terms they are much more extended (Fig. 15b). This is to be expected, considering the clumps we model are not strictly just high-mass protostars, but also formative groups and clusters of stars that will encompass many objects, including young low-mass stars (Sridharan et al. 2002). Note that the dust-free cavities around both high-mass and low-mass protostars extend far beyond the dust sublimation radius.

Figure 16a shows that for low-mass protostars, the densest envelopes also tend to be the most centrally peaked, and that there are no optically thick envelopes with shallow density gradients. The high-mass sample echoes this trend; the combination of high optical depth and strongly peaked power-law density profile suggests the centre of these cores must have a very high dust density.

The optical depth of low-mass cores also appears to be anti-correlated with the physical size of the envelope (Fig. 16b), where larger relative envelopes tend to have lower optical depth, a trend also suggested in the high-mass sample albeit

Fig. 16. Plots of the optical depth at $100\ \mu\text{m}$ (τ_{100}) and its relationship with the density profile power-law index (α ; left-hand plot) and dust-shell size ratio (Y ; right-hand plot). Low-mass and high-mass protostellar models are plotted by open circles and opaque rectangles respectively. Note that owing to the discrete set of models used to model the high mass sources, many markers for these objects overlap. Detailed investigation of the τ_{100} and Y data for the high mass sources, including least squares fitting excluding the extreme points, indicates the presence of an anti-correlation between these parameters.

with large scatter. This anti-correlation would suggest that high optical depths occur because the cores actually become more dense and not because the dust shells become larger to encompass more material.

5.4. Bolometric temperature

The bolometric temperature (T_{bol}) forms a diagnostic that helps characterise the evolutionary state of low-mass protostars (Myers & Ladd 1993) while SBSMW found that our sample was characterised by lower M/L than stars associated with UCHII regions, and suggested that M/L is in part a diagnostic of evolutionary status. In Fig. 17, we compare M/L to the T_{bol} for the sources we have modelled. No obvious correlation is found between M/L and T_{bol} , nor any relationship with B2002a evolutionary group, suggesting T_{bol} is not a useful diagnostic of high-mass protostars with current telescope resolution.

5.5. The missing IR flux

The majority of our best fits are essentially cold-component models. Removing the weighting in the SED fitting had little effect on this conclusion: it was generally very difficult to simultaneously match both the full SED and the $850\ \mu\text{m}$ spatial emission profiles. Even the more reasonable unweighted SED fits were not of the quality obtained using the weighted SED scheme. So it appears an additional, perhaps spatially distinct, hot dust component is needed to satisfy the short wavelength flux constraints.

In addition the possible presence of additional sources in these regions which contribute the IR emission, there are a number of possible sources of this emission which are not present in the current models. For example, Osorio et al. (1999) modelled accretion towards young high-mass stars with hot cores, and found that large accretion rates significantly increase the near-IR flux density. The large accretion rates assumed for high-mass stars suggests a large IR flux density should also be present. Additionally, the presence of a circumstellar disk or

Fig. 17. A plot of bolometric temperature (T_{bol}) against M/L ratio for our best-fit models. Models are grouped by B2002a evolutionary identifier (groups 1, 2 and 3) and plotted by faint open squares, triangles and circles respectively.

stochastic heating of small dust grains would alter the emission characteristics of the envelope and produce more short wavelength photons (e.g. Draine & Li 2001; Sellgren et al. 1983). However, by scaling the opacity of our model dust-grains to match our submm observations (Williams et al. 2004), we see that the dust envelopes are typically optically thick to radiation below $\sim 75\ \mu\text{m}$, and so even these additional processes will not satisfy the short-wavelength flux constraints without a low-opacity escape route. This could easily occur as the result of an asymmetric dust morphology or clearing by outflows, for example as seen towards IRAS 18556+0136 (Fuller et al. 2001).

It is also known that spherically symmetric models that do not account for accretion effects, dust clearing, and other inhomogeneities, tend to underestimate the short wavelength flux (van der Tak 2000), thus accretion, outflows, and other mechanisms may yet help satisfy the IR deficiency. The significance of these additional emission processes awaits high-resolution mid-IR and far-IR observations, which will determine whether the shorter wavelength emission is truly coincident with the submm detections, and also the advent of more detailed multi-dimensional radiative transfer models.

6. Conclusions

In this paper we have modelled the $850\ \mu\text{m}$ emission seen towards the SBSMW sample of candidate HMPOs using the one-dimensional radiative transfer code DUSTY (Izević et al. 1999). We used these models to examine the size and density structure of the dusty envelopes in which the high-mass protostars are embedded.

We found the spatial intensity profile and SED at long wavelengths ($>60\ \mu\text{m}$) can be well modelled by envelopes with power-law density structures (where $\rho \propto r^{-\alpha}$), and successfully modelled 36 sources within our sample. Using a careful selection of the area of sources modelled, we have shown that although good model fits may be obtained to the azimuthally averaged emission, the derived density profile can be significantly different from that derived from fitting radial slices in different

directions. In other words, fitting the azimuthal average emission may significantly (up to ± 1 in the power law index of the density profile) misrepresent the source structure. For three elongated sources comparison of the density profiles along the major and minor axes suggests the cores have a cylindrical-like density structure.

We find a mean density power-law index of $\bar{\alpha} = 1.3 \pm 0.4$. This result means we cannot eliminate the possibility that a significant proportion of cores may have a density structure similar to a logotropic density distributions ($\alpha = 1$). Our mean index falls below the value typically seen towards low-mass cores, and may provide further evidence to the argument for additional non-thermal support in high-mass cores compared to their low-mass counterparts (cf. van der Tak et al. 2000).

The mean index of our sample agrees (within the uncertainties) with the mean value derived independently from 1.2 mm observations of our sample (B2002a). Unlike B2002a however, we do not require power-law breakpoints to form fits to the spatial emission, which was a feature of the B2002a analysis. The mean index is also consistent with $\bar{\alpha}$ measured towards other samples of young high-mass stars and young low-mass stars. In addition, we find the envelopes bearing high-mass stars are considerably larger and denser than those bearing low-mass stars, existing between 10^{17} – $10^{18}/10^{19}$ cm from the protostar, with a mean optical depth at $100 \mu\text{m}$ of $\tau_{100} = 2.7$. The outer envelope size may define the mass reservoir from which high-mass stars form. A correlation between α and optical depth in models of low mass protostars is echoed by our models of high-mass sources. This correlation suggests that sources with the most strongly peaked power-law density profiles also tend to be the most dense. The high opacity of the models makes a typical high-mass dusty cocoon opaque to short-wavelength photons $< 75 \mu\text{m}$, and as a result, the majority of best models resemble the cold-component dust bodies proposed by Sridharan et al. (2002).

Previous models of young high-mass stars which were required to match short wavelength flux, favouring low optical depth and/or low inner temperatures. (e.g. Faison et al. 1998; Goedhart et al. 2000; Campbell et al. 2000; Churchwell et al. 1990; Hatchell et al. 2000.) We found it very difficult to find models that simultaneously fit the near-infrared and submillimetre flux constraints with the symmetric dust distributions investigated in this work. Models which fit the submillimetre data require high optical depths at $100 \mu\text{m}$, which then prevents the models from matching the near-infrared fluxes. This implies that the short wavelength emission seen towards our sample either originates from a separate hot dust component, spatially distinct from the central source, or there must be optically thin cavities which allow the short wavelength photons to escape. These possibilities are yet to be included in the models of these sources.

We find evidence that some of our sample may have smaller dust-free cavities than more evolved sources, yet we find no correlation between T_{inner} and Beuther et al. (2002a) evolutionary indicator, so it is unclear that the ratio of infall to outward radiative/outflow pressure changes significantly between pre-UCHII and UCHII cores. Considerable uncertainties remain, however, and further high-resolution temperature

tracer and mid-IR observations of this sample would be of considerable use in constraining the parameter space of our model SEDs – including most importantly the location of the inner boundary. This is of particular importance for future studies of these sources in which the modelling of the submillimetre continuum emission can provide the determination of the temperature and density profile needed to interpret molecular line observations of the sources.

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