An infrared-submillimeter study of star-forming regions selected by the ISOSS 170 µm survey

M. Hennemann, S. M. Birkmann, O. Krause, and D. Lemke

Max-Planck-Institut für Astronomie (MPIA), Königstuhl 17, D-69117 Heidelberg, Germany
e-mail: hennemann@mpia.de, birkmann, krause, lemke

ABSTRACT

Context. Using the ISOPHOT Serendipity Survey (ISOSS) at 170 µm a sample of galactic star-forming regions exhibiting very cold dust temperatures (< 20 K) and high masses (> 100 M⊙) has been established.

Aims. We characterise the star-forming content of five regions that were selected as potential sites for early stage high-mass star formation.

Methods. We use SCUBA (JCMT) observations in the submillimeter to identify the dense condensations of cold gas and dust. Sensitive mid- to far-infrared Spitzer observations with IRAC and MIPS allow us to detect associated young stellar objects. From the long-wavelength emission we derive dust temperatures and masses for the identified clumps. A sample of associated mid-infrared sources is investigated using infrared color-color diagrams and the comparison to a model SED grid to constrain their evolutionary stages and derive estimates for additional parameters like the central mass.

Results. In every region we identify between one and four submillimeter clumps with projected sizes between 0.1 and 0.4 pc. The dust temperatures range from 11.6 to 21.3 K and the estimated clump masses are 2 to 166 M⊙. Towards the majority of submillimeter peaks we find point sources in the near- to mid-infrared. Most are interpreted as low-mass young stellar objects but we also detect very red sources. They probably represent very young and deeply embedded protostars that continue to accrete clump material and may reach higher masses. Several candidate intermediate-mass proto- or pre-main-sequence stars embedded in the clumps are identified.

Conclusions. A subset of four clumps may be massive enough (> 100 M⊙) to form high-mass stars and accompanying clusters. The absence of stellar precursors with current masses in the high-mass regime leave the type of star formation occuring in the clumps unsettled. We confirm the presence of large fractions of cold material as derived from large-scale far-infrared measurements which dominates the emission of most clumps and suggests that the star-forming process will continue.

Key words. ISM: individual objects: ISOSS J19357+1950 - ISM: individual objects: ISOSS J19486+2556 - ISM: individual objects: ISOSS J20153+3453 - ISM: individual objects: ISOSS J20298+3559 - ISM: individual objects: ISOSS J22478+6357 - Stars: formation

1. Introduction

The origin of stars with masses of 10 M⊙ or more is a lively debated issue. Only recently approaches to establish an evolutionary sequence based on observations and theoretical considerations have been presented (Beuther et al. 2007; Zinnecker & Yorke 2007). However, the observational bases concerning the earliest phases in the formation process of high-mass stars remains sparse, as many studies target luminous infrared sources revealing embedded stellar precursors associated with hot as well as high-density gas. Younger objects that are sometimes addressed as infrared-quiet massive cores should be best detected using far-infrared and submillimeter dust continuum surveys as they are assumed to contain large amounts of cold material. Furthermore, the identification of extinction features against the galactic mid-infrared background provides a number of candidate objects commonly referred to as infrared dark clouds (IRDCs). Only a relatively small number of candidate sources have been investigated in detail (recently e.g. Beuther & Steinacker 2007; Rathborne et al. 2007; Birkmann et al. 2007) but also results of larger-scale studies suggest that the lifetimes of massive prestellar cores are very short (Motte et al. 2007).

The thermal emission from cold dust (< 20 K) peaks in the wavelength range beyond the IRAS 100 µm limit. The 170 µm ISOPHOT Serendipity Survey (ISOSS) (Lemke et al. 1996; Bogun et al. 1996; Stickel et al. 2007) carried out during the ISO mission (Kessler et al. 1996) provides the first large-scale survey in this range and is well-suited to search for extremely young and massive star-forming regions. Selecting compact 170 µm sources (FWHM < 3.5′) that are associated with an IRAS 100 µm point source (Beichman et al. 1988) and molecular gas emission, a sample of more than 50 massive candidate sources has been identified (see Krause 2003; Krause et al. 2004 and references therein). The large-scale average dust temperatures derived from the flux ratios at 170 and 100 µm are about 18 K or lower and the resulting mass-luminosity ratios are M/L ∼ 0.6 M⊙/L⊙ implying early stages in the process of star formation (cf. Sridharan et al. 2002). In order to explore the physical conditions in this unique sample of cold and massive star-forming regions and to search for possible high-mass prestellar cores, a multi-wavelength follow-up survey has been launched. The presence of very young massive clumps and cores has been confirmed for the regions ISOSS J20298+3559 (Krause et al. 2003), ISOSS J18364-0221 (Birkmann et al. 2006) and ISOSS J23053+5953 (Birkmann et al. 2007). In this paper we report on observations of four more ISOSS star-forming regions and extend the study of ISOSS J20298+3559.
Our continuum observations with high spatial resolution covering the submillimeter to near-infrared wavelength range allow us to characterize the detailed star-forming content. In the submillimeter we trace the thermal dust emission and identify compact condensations. To constrain their evolutionary stage we have conducted mid- and far-infrared observations using Spitzer. The long-wavelength data in the far-infrared and submillimeter is used to estimate the dust temperatures and total masses of the clumps. The sensitive mid-infrared data also reveal very young associated stellar objects. Additional deep near-infrared images provide a good assessment of source confusion. For the detected young stellar objects we perform an evolutionary classification from their infrared colors. In the Discussion section we further characterize a subset using radiative transfer models.

2. Observations, Data Reduction and Analysis

2.1. Submillimeter continuum emission

Submillimeter continuum jiggle maps at 450 \(\mu\)m and 850 \(\mu\)m were obtained with SCUBA (Holland et al. 1999) at the James Clerk Maxwell Telescope (JCMT) in July 2001 and May 2003 under good atmospheric transmission conditions ($T_{500} < 0.2$). Reduction was done using the ORAC-DR (Jenness & Economou 1999) and SURF (Jenness & Lightfoot 1998) software. Photometric calibration is based on maps of Uranus acquired shortly before or after the observations. Further analysis was done using the MIRIAD (Sault et al. 1995) software package and followed the procedure described in Sandell & Weintraub (2001): To account for the deviations of the JCMT beam from a single Gaussian we used the Uranus maps to construct symmetric beam models and deconvolve the maps of the target regions. The derived beam sizes are 7.8 – 8.8” at 450 \(\mu\)m and 14.7 – 15.1” at 850 \(\mu\)m. The maps are then restored using a gaussian of 8” and 14”, respectively. By fitting gaussian components to the restored maps we first derive submillimeter continuum fluxes and deconvolved source sizes at 450 \(\mu\)m. We then use these sizes convolved with the 14” gaussian to extract 850 \(\mu\)m fluxes in order to include emission from the same regions only. The photometric accuracy is estimated to be 30% at 450 \(\mu\)m and 20% at 850 \(\mu\)m and the pointing uncertainty of the submillimeter maps is 2” rms.

2.2. Near-infrared emission

Near-infrared images in J, H and Ks were taken with the Calar Alto 3.5 m telescope using the two prime focus wide field cameras Omega2000 (Baumeister et al. 2003) and OmegaPrime (Bizenberger et al. 1998). Omega2000 features a field of view (FOV) of 15.4×15.4 arcmin\(^2\) with a pixel scale of 0.4496” pix\(^{-1}\), while the FOV for OmegaPrime is 6.8×6.8 arcmin\(^2\) with a pixel scale of ~ 0.4” pix\(^{-1}\). The exposure time in the broad band filters was 20 minutes each. The exposures were dithered on source to allow for sky subtraction. The reduction and photometry was done using IRAF (Tody 1993) and GAIA\(^1\) and the photometric calibration for J, H, and Ks is based on the 2MASS point source catalog.

2.3. Mid- and far-infrared emission

The Spitzer (Werner et al. 2004) observations include IRAC (Fazio et al. 2004) imaging in all four photometric bands, MIPS (Rieke et al. 2004) imaging at 24 \(\mu\)m and 70 \(\mu\)m and the MIPS spectral energy distribution (SED) mode. For the imaging observations the basic flux calibrated data (BCD) of the Spitzer Science Center (SSC) pipeline was used for further data reduction and analysis. The calibration uncertainties of the data are about 2% for IRAC (Reach et al. 2003), 4% for MIPS 24 \(\mu\)m (Engelbracht et al. 2007) and 10% for MIPS 70 \(\mu\)m (Gordon et al. 2007). Cosmetic corrections and astrometric refinement was performed with the MOPEX software (Makovoz & Marleau 2005) and final images were combined using scripts in IRAF. Aperture photometry and PSF fitting was done with the aperture corrections given on the SSC website\(^2\). The MIPS SED mode calibration is based on a spectrum of \(\alpha\) Boo (Low et al. 2005) and the measured MIPS 70 \(\mu\)m fluxes. The resulting photometric accuracy is estimated to be 5% (IRAC), 10% (MIPS 24), and 20% (MIPS 70 and SED).

3. Observational results: Submillimeter emission morphology and associated mid-infrared sources

The five ISOSS regions are listed in Table 1 and displayed in Figs. 1 to 5. In the following we describe their individual submillimeter morphologies and point out the associated 24 \(\mu\)m sources. On the IRAC and near-infrared maps those sources for which singular counterparts can be identified at shorter wavelengths are marked.

3.1. ISOSS J19357+1950

In this region three submillimeter emission components are resolved at 450 \(\mu\)m, two adjacent parts (SMM1 North and South) and a south-western part (SMM2) (Fig. 1). They have deconvolved FHWM sizes of about 19", 16" and 20” which correspond to 0.31–0.39 pc. An arc-shaped extended emission feature that stretches from South-east to North-west is visible at 24 \(\mu\)m. Two 24 \(\mu\)m point sources are detected associated with SMM1 North, for SMM1 South and SMM2 one and two sources are present respectively. Both SMM1 North and South are also coincident with emission at 70 \(\mu\)m but are not resolved individually. At the location of SMM2 no distinct 70 \(\mu\)m feature is detected.

3.2. ISOSS J19486+2556

Three submillimeter clumps are detected in this region: They are located along a chain from north-east to south-west and termed SMM1 to SMM3 (Fig. 2). All three appear compact in the submillimeter. The deconvolved FHWM diameters are about 16” (SMM1), 10” (SMM2) and 15” (SMM3) at 450 \(\mu\)m. The corresponding length scales are 0.14 – 0.22 pc. Both SMM2 and SMM3 are associated with bright 24 and 70 \(\mu\)m sources. In the case of SMM2, several objects are detected at 24 \(\mu\)m and the brightest one coincides with the submillimeter peak as well as with the 70 \(\mu\)m source. For SMM3, one source at 24 and 70 \(\mu\)m is located at the submillimeter peak. In addition, two areas of extended 24 and 70 \(\mu\)m emission are found, one in the south-east of SMM2 and a second one towards the southern rim of SMM3. The first one is not associated with submillimeter emission. Only a faint source at 24 \(\mu\)m is detected towards the center of SMM1 and it is not associated with compact 70 \(\mu\)m emission.

---

\(^1\) http://star-www.dur.ac.uk/~pdraper/gaia/gaia.html

\(^2\) http://ssc.spitzer.caltech.edu
Table 1. Observed ISOSS star-forming regions.

| Region ISOSS     | Assoc. IRAS point source | RA (J2000)   | DEC (J2000)   | Distance\(^a\) in kpc | T\(_{\text{FIR color}}\)\(^b\) in K |
|------------------|--------------------------|--------------|--------------|------------------------|----------------------------------|
| J19357+1950      | 19335+1944               | 19:35:45.9   | +19:50:58    | 4.0                    | 17.5                             |
| J19486+2556      | 19465+2549               | 19:48:36.8   | +25:56:55    | 2.9                    | 18.0                             |
| J20153+3453      | 20134+3444               | 20:15:20.9   | +34:53:53    | 2.0                    | 19.0                             |
| J20298+3559      | 20278+3549               | 20:29:48.3   | +35:59:24    | 1.8                    | 16.0                             |
| J22478+6357      | 22460+6341               | 22:47:54.1   | +63:57:11    | 4.1                    | 15.4                             |

\(^a\) Kinematic distances obtained using the galactic rotation model of Brand & Blitz (1993) and identification of kinematically associated molecular cloud complexes (Krause 2003).

\(^b\) T\(_{\text{FIR color}}\) is derived from the far-infrared flux ratios at 100 \(\mu\)m (IRAS) and 170 \(\mu\)m (ISOSS).

Fig. 1. Observations of the region ISOSS J19357+1950. The left panel shows the 24 \(\mu\)m map and the overlaid contours show the SCUBA 450 \(\mu\)m emission. The mid panel shows a color composite of the IRAC images. The right panel is a JHK\(_s\) color composite using OmegaPrime and Omega2000 observations. The circles surround the sources investigated in the Analysis section.

Fig. 2. Observations of the region ISOSS J19486+2556. Same arrangement and symbols as in Fig. 1.

3.3. ISOSS J20153+3453

This region contains a single submillimeter clump clearly detected in both SCUBA bands (Fig. 3). The deconvolved 450 \(\mu\)m FWHM extension is about 18" \(\times\) 14" i.e. the projected diameter of the clump is around 0.16 pc. In the 24 \(\mu\)m band two point-like sources surrounded by extended emission are detected towards the north-western limb of the submillimeter clump. The brighter one is located among a cluster of sources seen at shorter wavelengths. At 70 \(\mu\)m none of these are resolved individually, they blend into a single slightly extended source. The submillimeter emission peak is offset from the brighter point source by 11".

3.4. ISOSS J20298+3559

This region has been studied in detail in Krause et al. (2003). Four submillimeter emission peaks are found in this region: Two of them are joined by extended emission (SMM1 and SMM2) while SMM3 and SMM4 are offset to the west (Fig. 4). SMM4 has not been discussed in Krause et al. (2003). The sizes of the
4 M. Hennemann et al.: An infrared-submillimeter study of star-forming regions selected by the ISOSS 170 µm survey

Fig. 3. Observations of the region ISOSS J20153+3453. Same arrangement and symbols as in Fig. 1.

Clumps SMM1 and SMM3 are approximately 0.14 and 0.17 pc, SMM2 is unresolved (< 0.07 pc) and SMM4 is more extended. The deconvolved FWHM diameter is roughly 39″ corresponding to 0.34 pc. SMM1, SMM2 and SMM4 are associated with emission at 70 µm. SMM3 was not covered by our 70 µm maps. Two 24 µm point sources are detected towards SMM2 and one towards SMM4. SMM1 and SMM3 have faint counterparts at 24 µm.

3.5. ISOSS J22478+6357

The submillimeter emission in this region traces an elongated clump (SMM1) that is resolved in an eastern and a western component at 450 µm (Fig. 5). The deconvolved 450 µm FWHM extensions of these are ~ 7″ and ~ 12″, corresponding to roughly 0.14 and 0.24 pc. At 24 µm, several point sources are associated. The brightest are located at the eastern and to the southern limb of the western submillimeter peaks. The 70 µm map reveals emission that coincides with the submillimeter peaks and with the 24 µm sources.

4. Analysis

We first present the analysis of the long-wavelength observations towards the star-forming regions and then address the associated infrared sources. The extracted fluxes in the far-infrared and submillimeter are listed in Table 2. In Figs. 6, 7, 8, 9 and 10 the spectral energy distributions (SEDs) of the detected clumps are sketched.

4.1. Far-infrared spectral slopes

The examination of the SEDs compiled for the seven detected clumps towards which MIPS SED observations have been performed shows that the spectral slopes at wavelengths around 70 µm and below do not resemble a single thermal emission component that would reproduce the submillimeter fluxes. It presumably originates from warmer dust components or transiently heated very small grains (cf. Birkmann et al. 2007; Rawlings et al. 2005). The spectral slopes (d log(λFλ)/d log(λ)) vary in the range 0.3 – 2.0 for 70 µm < λ < 94 µm.

4.2. Clump dust temperatures and masses

To characterize the cold component of dust (and gas) that gives rise to the emission at long wavelengths, we assume that it can be reproduced by isothermal dust emission. As noted above, the fluxes at wavelengths around 70 µm and below do not conform with this assumption and we therefore use the datapoints at 93, 450 and 850 µm to estimate the dust temperature. In that respect we also assume that the emission at these wavelengths is optically thin and can be approximated by a modified Planck spectrum. We use the dust opacities given in Ossenkopf & Henning (1994) for a MRN distribution either without ice mantles, with thin and with thick ice mantles (κ850µm = 0.6 – 1.4 cm²/g) corresponding to emissivity indices of β = 1.81 – 1.85 at long wavelengths. The dust-to-gas mass ratio is assumed to be 1/100. In the cases where no MIPS SED measurements are available, we extrapolate the 70 µm flux to 93 µm allowing for spectral slopes of 0.3 and 2.0 (adopting the measured extremes). We list the resulting range of dust temperatures and gas masses for each clump in Table 2. The fitted curves are shown in Fig. 6, 7, 8, 9 and 10.
4.3. Associated infrared sources

We detect a number of sources at 24 μm and shorter wavelengths that are associated with the submillimeter clumps. To evaluate their nature and relationship with the submillimeter condensations we select the sources marked in the mid and right panels of Fig. 4 to 5 for which we can identify singular counterparts. At distances of 2 – 4 kpc the resolution achieved in the Ks band corresponds to 1600 – 3200 AU and we can only probe the confusion of sources on scales larger than these. For sources that show no near-infrared counterpart the IRAC resolution at 3.6 μm which corresponds to 3000 – 6000 AU limits the search for multiplicity. In addition we check for optical counterparts in Second Digitized Sky Survey DSS2-red maps. Sources without optical counterpart are best candidates to represent embedded objects and therefore the association with the molecular and dusty clumps is presumably no projection effect. However, the actual positions of the sources with respect to the clumps and the foreground extinctions are unknown.

Robitaille et al. (2006) present a grid of young stellar objects (YSOs) model SEDs which has been used to analyze mid-infrared sources detected with Spitzer in star-forming regions (Indebetouw et al. 2007; Shepherd et al. 2007). Utilizing a Monte-Carlo radiative transfer code, more than 20,000 2D models were computed for ten inclinations each. The different evolutionary phases in the modelled parameter space are ordered according to the Class system (André 1994) into stages: Stage 0/I (hereafter: Stage I) are very young objects that are deeply embedded in an extended envelope with a cavity surrounding an accretion disk, Stage II contains disk-dominated models and Stage III represents star-dominated systems. Via a web interface measured fluxes of individual sources can be put into a model SED fitting routine to constrain source parameters (Robitaille et al. 2007) and we make use of this below in the Discussion section.

The color-color diagram [3.6]-[5.8] versus [8]-[24] (Fig. 23 in Robitaille et al. 2006) offers a good distinction between the stages. These colors have also been compiled in Reach et al. (2004) for a number of young stellar objects in the Elephant Trunk Nebula which have been classified before according to the Class system (see Reach et al. 2004, and references therein). For a verification of the color assessment we plot their data and the regions corresponding to the Stages proposed by Robitaille et al. (2006) in the upper left panel of Fig. 11. The foreground extinction appears to be small for these sources. The Class I/0 and I sources fall into the corresponding Stage I region with one exception. The colors of Class I/II and II sources lie in the Stage
**Fig. 6.** Spectral energy distributions of the submillimeter sources in the region ISOSS J19357+2556. The diamonds represent photometric data obtained with MIPS (70 µm) and SCUBA (450 and 850 µm) and extrapolated data at 93 µm for SMM1 South and SMM2. Histogram-like bars show the error range of the MIPS SED spectrophotometry (53-93 µm) for SMM1 North. The lines show modified blackbody fits for λ ≥ 93 µm using different dust opacities (solid: no ice mantles, dotted: thick ice mantles, dashed: thin ice mantles). For SMM1 South and SMM2 two sets of curves are shown for spectral slopes of 0.3 and 2.0 in 70 ≤ λ ≤ 93 µm.

**Fig. 7.** Spectral energy distributions of the submillimeter sources in the region ISOSS J19486+2556. The diamonds represent photometric data obtained with SCUBA (450 and 850 µm). Histogram-like bars show the error range of the MIPS SED spectrophotometry (53-93 µm), for SMM1 upper limits are plotted with triangles. The lines show modified blackbody fits for λ ≥ 93 µm using different dust opacities (solid: no ice mantles, dotted: thick ice mantles, dashed: thin ice mantles).

II region with one exception. The colors of the debris disk object β Pictoris place it on the border between the Stage II and III regions. These accordances support the utility of the colors for classification and we apply this method to our source samples to get an estimate of their evolutionary status. However, due to the presence of a significant amount of dust in the regions, an enhanced extinction is expected for our sources. In the remaining five panels of Fig. 11 the infrared colors of the sources marked (and numbered) in Fig. 1 to 5 are plotted. Sources without optical counterpart in DSS2-red maps are marked with crosses. Most of the evaluated sources exhibit colors lying in the Stage II region or in the vicinity of the Stage I/II transition. Interestingly, a few sources show very red colors that are consistent with Stage I even if a foreground extinction of A_V ≥ 100 is assumed. Exhibiting [8]-[24] > 5, these sources are distinct from the sample in the upper left panel. Two red sources, Source 1 in ISOSS J19486+2556 and Source 6 in ISOSS J22478+6357, apparently show enhanced 5.8 µm emission but still lie within the Stage I region. Both are very faint in the near-infrared.

Several sources are associated with “fuzzy” green features in the IRAC composite images and/or extended emission features in the near-infrared: Source 2 in ISOSS J19486+2556, Source 2 in ISOSS J20153+3453, Source 8 in ISOSS J20298+3559 and also towards the SMM3 peak in ISOSS J19486+2556, where we cannot identify the appropriate counterparts to the detected 24 µm source, and towards the SMM1 peak in ISOSS J20298+3559, where the 24 µm source shows no counterparts at shorter wavelengths. These features likely trace outflow activity from young accreting objects which gives rise to shock-excitation of molecular hydrogen and CO. However, also atomic hydrogen Br α line emission can contribute to the IRAC 4.5 µm flux.

The most prominent features in the IRAC composite image of ISOSS J19486+2556 are two extended red emission features east of SMM2 and south of SMM3 which are also visible at the MIPS wavelengths. In the near-infrared very red objects are detected that are located towards the centers of the features which themselves are not traced. Extended low-density dust heated to higher temperatures could give rise to the mid- and far-infrared emission.

In the panel of Fig. 11 corresponding to ISOSS J20298+3559 we also plot the approximate colors of the brightest source in the region, located western of SMM1. It has been investigated in detail in [Krause et al. (2003)] and classified as Herbig B2e star that is accreting from a disk which is optically thick. The 8 and 24 µm images seem to show non-linear effects due to the brightness of the source which may affect the derived colors corresponding to Stage II.
Fig. 9. Spectral energy distributions of the submillimeter sources in the region ISOSS J20298+3559. The diamonds represent photometric data obtained with MIPS (70 µm) and SCUBA (450 and 850 µm), extrapolated data at 93 µm for SMM1 and SMM2 and the datapoint at 1.2 mm for SMM1. Histogram-like bars show the error range of the MIPS SED spectrophotometry (53-93 total emission at the shortest wavelengths used (93 µm for SMM4. The lines show modified blackbody fits for the mean dust temperatures. Setting the dust temperature to a canonical value of 20 K results in a decrease of the mass by up to a factor of about two for the coldest temperatures, but would require high optical depths at wavelengths around 100 µm to be consistent with the measured fluxes. However, the required mass scales similarly to the optical depth. It seems therefore unlikely that this effect causes errors in the mass estimation of more than a factor of two.

The distances to the regions are mainly derived from radial velocities and carry therefore some uncertainty. In Krause et al. (2003) the distance to ISOSS J20298+3559 has been constrained by an extinction study to 1.8 ± 0.3 kpc. We estimate the other distances to be reliable within ~1 kpc which results in possible mass changes by factors of 1.3 to 1.8. Another uncertainty factor of the order of two for the mass estimate arises from the unknown dust composition, e.g. the dust opacities given by Ossenkopf & Henning (1994) are about five times higher than those used for the calculation of the model SED grid. It is obvious from the SED diagrams that dust models corresponding to a lower value of the emissivity index would increase the number of variable parameters for the fit above the number of datapoints used. From

Table 2. Long-wavelength emission and derived properties of the cold component of the detected clumps.

| Region ISOSS... | Clump | Total flux (Jy) | Size (pc) | Dust temperature (K) | Gas mass (M⊙) |
|-----------------|-------|----------------|-----------|----------------------|---------------|
| J19357+1950     | SMM1 N | 3.3 6.0 2.1 0.40 0.37 16.6 – 18.7 | 54 – 92 |
|                 | SMM1 S | 0.57 0.80 – 1.3a 1.0 0.21 0.31 14.1 – 16.5 | 34 – 66 |
|                 | SMM2   | 0.21 0.30 – 0.47a 1.9 0.35 0.39 12.0 – 13.7 | 85 – 166 |
| J19486+2556     | SMM1   | < 0.15 < 0.26 2.2 0.51 0.22 11.6 – 12.5b | 69 – 123b |
|                 | SMM2   | 2.7 4.6 2.1 0.38 0.14 16.1 – 18.1 | 28 – 49 |
|                 | SMM3   | 7.4 11 4.1 0.59 0.21 16.8 – 19.0 | 46 – 79 |
| J20153+3453     | SMM1   | 13 17 12 2.1 0.16 15.3 – 17.0 | 87 – 149 |
| J20298+3559     | SMM1   | 1.7 2.5 – 3.7a 1.3c 0.23c 0.14c 15.8 – 18.8d | 6 – 13d |
|                 | SMM2   | 1.1 1.6 – 2.4a 0.31c 0.09c 0.07c 17.3 – 21.3 | 2 – 3 |
|                 | SMM4   | 0.41 0.81 3.9 1.0 0.34 12.1 – 13.2 | 46 – 80 |
| J22478+6357     | SMM1 E | 0.80 1.6 1.0 0.35 0.14 14.7 – 16.4 | 47 – 81 |
|                 | SMM1 W | 0.72 1.0 – 1.6a 1.8 0.47 0.24 13.4 – 15.5 | 79 – 153 |

a Extrapolated values.
b Derived using upper limit fluxes.
c Flux values and sizes from Krause et al. (2003).
d Derived from listed fluxes and 0.075 Jy at 1.2 mm (Krause et al. 2003).

5. Discussion

5.1. The clump population

Our simple approach to reproduce the long-wavelength emission towards the sample of submillimeter clumps by one component neglects any effects of the density and temperature distributions within the clumps and the assumption of optically thin emission may be violated in the far-infrared if the (column) density is high enough. Assuming a density profile that is flat in the innermost region of 100 AU radius, follows a power-law ($\rho \propto r^{-\alpha}$ with $\alpha = 1.5$) in between and is cut-off exponentially at 20,000 AU, an optical depth of unity is reached at about 100 µm for a 100 M⊙ condensation (dust opacities from Draine & Lee (1984); Steinacker, private communication). Therefore we may underestimate the total emission at the shortest wavelengths used (93 µm) and also the mean dust temperatures. Setting the dust temperature to a canonical value of 20 K results in a decrease of the mass by up to a factor of about two for the coldest temperatures, but would require high optical depths at wavelengths around 100 µm to be consistent with the measured fluxes. However, the required mass scales similarly to the optical depth. It seems therefore unlikely that this effect causes errors in the mass estimation of more than a factor of two.
Fig. 11. IRAC and MIPS infrared color-color diagram. The regions where most models are Stage I, II and III according to Robitaille et al. (2006) are shaded from dark to light grey. The vectors show an extinction of $A_V = 20$ (Indebetouw et al. 2005). In the upper left panel young stellar objects corresponding to different evolutionary stages from Reach et al. (2004) are plotted. In the five remaining panels the mid-infrared sources associated with submillimeter emission in the ISOSS star-forming regions are drawn (diamonds, numbering as in Figs. 11-15). The sources without optical counterpart are marked by crosses. In the panel corresponding to ISOSS J20298+3559 the approximate colors of the Herbig B2e star are represented by the triangle.

The derived dust temperatures (see Table 2) lie between 11.6 and 21.3 K, approximately in the same range as the far-infrared color temperatures from ISO and IRAS fluxes of the whole regions (see Table 1). In comparison to other studies, the values are consistent with those of cold dust components derived and assumed for young dense clumps (e.g. Beuther & Steinacker 2007; Sridharan et al. 2005; Enoch et al. 2007).

The estimated masses that reside in these cold dust and gas components range from $2 \, M_\odot$ up to $166 \, M_\odot$. Taking the mass estimates at face value, four of the clumps may be massive enough ($> 100 \, M_\odot$) to form a high-mass star and an accompanying cluster, if one assumes that a fraction of 10% of the total mass ends up in massive stars (Zinnecker & Yorke 2007). The star formation efficiency is observationally not well constrained on the scales of individual clumps.

From the source sizes in Table 2 volume-averaged densities have been derived for our clump sample under the assumption of spherical symmetry. The resulting densities are $4 \cdot 10^4 \, cm^{-3} < n_H < 10^6 \, cm^{-3}$ with a median value of $2 \cdot 10^5 \, cm^{-3}$. Compared to studies of dense condensations found in IRDCs (Rathborne et al. 2006: median density $3 \cdot 10^4 \, cm^{-3}$) and in Cygnus X (Motte et al. 2007: median density $2 \cdot 10^5 \, cm^{-3}$) the evaluated clumps seem to be more similar to the latter sample based on a millimeter continuum survey. Both the mentioned samples seem to contain candidate objects representing very early stages of massive star formation (e.g. massive infrared-quiet cores). For the sample of Beuther et al. (2002) based on IRAS measurements and containing luminous infrared sources a lower mean density of $9 \cdot 10^3 \, cm^{-3}$ is recalculated in Motte et al. (2007). The direct comparison of these densities may be affected by systematically different derivation methods, but it suggests that the source selection based on longer wavelengths gives access to presumably less evolved sources. In the present case the $170 \mu m$ band measurements constrain the average dust temperature to lower values than those that can be inferred from the IRAS bands.

5.2. The nature of the $24 \mu m$ sources

The majority of the clumps appear in a stage where $24 \mu m$ sources are present. In the following we discuss their ability to generate high-mass star progenitors and evaluate selected subsamples in more detail. During their formation high-mass stars develop high luminosities: According to the approach of McKee & Tan (2003) values above $100 \, L_\odot$ are reached already when one solar mass has been accreted. The corresponding timescale is on the order of several $10^4$ years. Therefore young high-mass stars should stand out as luminous sources. However, due to the reprocessing of the radiation at short wavelengths by the surrounding dusty envelopes only a fraction of the luminosity is released at the infrared wavelengths we probe (here we consider $\lambda \leq 24 \mu m$). If the source is deeply embedded, we will expect its infrared colors to be very red and the emission at op-
clumps and probably will not be able to accrete enough material to end up as high-mass stars. Furthermore, in [Kruse et al. (2003)] the submillimeter source SMM1 in ISOSS J20298+3559 is found to be a candidate Class 0 object. We detect a 24 µm source towards this peak which is not seen at shorter wavelengths. Associated outflow-tracing emission supports the classification as young protostellar object.

Source 5 in ISOSS J19357+1950 is located towards the massive clump SMM2. We apply the online model fitter using the fluxes including upper limits in the H band, at 70, 450 and 850 µm. Source 2 found towards the massive clump ISOSS J20153+3453 SMM1 exhibits very red colors and is associated with a possible outflow. The online model fitter is fed with the fluxes including upper limits in the J band, at 70, 450 and 850 µm. For SMM1 in ISOSS J20298+3559 we input the fluxes measured at 24, 70, 450 and 850 µm and upper limits in the IRAC bands and in the Ks band. The range of possible foreground extinction is selected to $A_V \leq 500$. The fitting results for these three sources are listed in Table 3. From the inspection of the SED plots we establish a cut-off value of $\chi^2$ (per datapoint) to select the models that fit the datapoints within reasonable margins. We also give the total extinction to the central source by combining the fitted foreground extinction with compensating foreground extinctions. The results are consistent with the interpretation of the sources as young embedded stellar precursors. The observed outflow activity signatures accord with high accretion rates for the latter two sources. In the cases of ISOSS J19357+1950 SMM2 and ISOSS J20153+3453 SMM1 the estimated large total masses of around 100 M$_\odot$ residing in cold components of dust and gas would in principle allow ongoing accretion and the build-up of high-mass stars. However, due to the multiplicity of near-infrared sources that are detected in the vicinity of ISOSS 20153+3453 SMM1 the further evolution of this object is not straightforward. Towards ISOSS J19357+1950 SMM2 there also is a second more evolved source nearby. In the third case the mass estimate of about 10 M$_\odot$ for ISOSS J20298+3559 SMM1 is consistent with the source being an intermediate-mass star precursor.

The remaining very red candidate Stage I source located towards the clump SMM1 in the region ISOSS J19486+2556 is particularly interesting because of the low infrared luminosity in comparison to the submillimeter, making it a candidate for a young and deeply embedded object. We input the photometric data into the online model fitter including upper limits in the $K_s$ band, at 70, 450 and 850 µm. We choose a cut-off at $\chi^2 < 49.6$ to select the acceptable fits. The results for this source are ambiguous: Among the selected models are several belonging to the Stage I category with central source masses of about 0.1 M$_\odot$ but also a majority of Stage II models with central source masses between 3 and 4.5 M$_\odot$, both with and without envelopes. There is no significant difference in the fitted total extinction towards the central sources. We therefore cannot assess and constrain the parameters of this source.

5.2.2. Evolved young stellar objects

We also detect sources whose SEDs are dominated by emission at mid-infrared wavelengths which exhibit higher total luminosities and may represent more massive YSOs. By comparing the spectral energies at 24 µm and 70 µm we find two candidate sources, located towards SMM4 in ISOSS J20298+3559 (Source
Table 3. Results of the SED fitting for three very red young stellar objects.

| Region ISOSS… | J19357+1950 | J20153+3453 | J20298+3559 |
|---------------|-------------|-------------|-------------|
| Source        | 5           | 2           | 2           |
| Associated clump | SMM2    | SMM1        | SMM1        |
| Selected cut-off | $\chi_d < 14.2$ | $\chi_d < 9.3$ | $\chi_d < 12.3$ |
| Fitted models | Stage I     | Stage I     | Stage I     |
| Total extinction | $A_V \sim 85$ | $A_V \sim 100$ | $A_V > 200$ |
| Central mass ($M_\odot$) | 0.2 – 2.1 | 0.7 – 2.3 | 0.2 – 4.6 |
| Envelope accretion rate ($M_\odot$/yr) | $1.6 \cdot 10^{-6} – 8.9 \cdot 10^{-5}$ | $1.5 \cdot 10^{-6} – 3.4 \cdot 10^{-4}$ | $4 \cdot 10^{-6} – 7 \cdot 10^{-4}$ |

Table 4. Results of the SED fitting for two evolved young stellar objects.

| Region ISOSS… | J20298+3559 | J22478+6357 |
|---------------|-------------|-------------|
| Source        | 8           | 3           |
| Associated clump | SMM4    | SMM1 East   |
| Selected cut-off | $\chi_d < 3.3$ | $\chi_d < 2.1$ |
| Fitted models | Stage II$^a$ | Stage II$^b$ |
| Total extinction | $6 < A_V < 9.4$ | $29 < A_V < 41$ |
| Total luminosity ($L_\odot$) | $\sim 150$ | $\sim 2000$ |
| Central mass ($M_\odot$) | 3.2 – 4.9 | 6 – 8.5 |
| Preferred inclination | low | - |
| Disk mass ($M_\odot$) | $4 \cdot 10^{-6} – 10^{-4}$ | $10^{-5} – 10^{-1}$ |
| Accretion rate ($M_\odot$/yr) | $10^{-11} – 10^{-6}$ | $5 \cdot 10^{-11} – 2 \cdot 10^{-5}$ |
| System age (yr) | $10^6 – 10^7$ | $10^6 – 6 \cdot 10^9$ |

$a$ $M_{\text{disk}}/M_\odot \geq 7.7 \cdot 10^{-7}$
b $M_{\text{disk}}/M_\odot \geq 9.5 \cdot 10^{-7}$

8) and SMM1 East in ISOSS J22478+6357 (Source 3). We also use the fluxes from [Krause et al., 2003] for the I, J, H and Ks bands as well as upper limits at 70, 450 and 850 µm for the former and upper limits in the J band, at 70, 450 and 850 µm for the latter source. The fitting results are compiled in Table 4.

We consider the first source to be an embedded proto- or pre-main-sequence star of intermediate mass as also suggested by [Krause et al., 2003]. It probably has been formed in the SMM4 clump. The results for the second source are consistent with the source representing an evolved YSO of at least intermediate mass that is still embedded and presumably has been formed within the clump SMM1 East.

6. Conclusions

We have analysed multi-wavelength observations of five star-forming regions that were identified using the ISOPHOT Serendipity Survey at 170 µm. From the discussed results we infer:

1. We found one to four compact (~ 0.2 pc) submillimeter condensations in every region that represent molecular clumps containing a cold component of gas and dust. The dust temperature estimates vary between 11.6 and 21.3 K and accord with the large-scale color temperatures measured in the far-infrared.

2. The resulting estimated clump masses that reside in these cold components range from 2 to 166 $M_\odot$. Four out of twelve clumps may be massive enough (> 100 $M_\odot$) to be promising candidate birthplaces for high-mass stars.

3. We identify multiple associated mid-infrared sources for the majority of the clumps suggesting that they embody significant density substructures on smaller scales than probed by the submillimeter observations (> 0.1 pc). Since the emission of most clumps is dominated by the cold material we expect thriving star formation from further collapse of overdensities.

4. Most of the associated sources are considered as low-mass young stellar objects in an evolutionary state later than Class 0/I partly embedded in the clumps where they have formed.

5. In the region ISOSS J19357+1950 we find a massive clump of around 100 $M_\odot$. A probably deeply embedded accreting Class 0/I protostar of ~ 1 $M_\odot$ is detected adjacent to a more evolved young stellar object. Similarly, in ISOSS J20153+3453 one massive clump of about 100 $M_\odot$ is present and a cluster of sources is detected in the vicinity containing a presumably deeply embedded accreting protostar with a current mass of ~ 1.5 $M_\odot$. Its evolutionary state corresponds to Class 0/I and there is evidence for outflow activity from this object.

6. The source SMM1 in ISOSS J20298+3559 probably represents a young accreting intermediate-mass star precursor embedded in a molecular clump of ~ 10 $M_\odot$. Towards SMM4 in the same region we identify an embedded proto- or pre-main-sequence star of 3.2 – 4.9 $M_\odot$ that likely evolved from the associated clump of ~ 60 $M_\odot$.

7. In the region ISOSS J22478+6357 a candidate protostar of 6–8.5 $M_\odot$ is found that is embedded in the associated SMM1 East clump (~ 60 $M_\odot$).

8. We do not detect stellar precursors that could have current masses of 10 $M_\odot$ or more. Therefore we cannot be sure whether such objects will emerge within the identified clumps. However, the presence of intermediate-mass protostar or pre-main-sequence star candidates and the large clump masses indicate that one can expect that also high-mass stars are formed in these systems.

9. Our study reveals that the search for regions containing large fractions of cold material in the far-infrared has successfully identified star-forming regions associated with cold and massive clumps. Compared to sources selected at shorter wavelengths they may represent less evolved stages of high-mass star-formation and in that respect substantial impact can be expected from future (space) missions like Herschel and Planck. Furthermore this study demonstrates that the detailed star-forming content can only be accessed with a multi-wavelength approach including sensitive mid- and far-infrared observations.

Acknowledgements. Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA. The ISOSS was supported by funds from the DLR, Bonn. Based on observations collected at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max Planck Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC), and on observations with the James-Clerk-Maxwell Telescope (JCMT) as well as on observations made with the Spitzer Space Telescope, which is operated by the
