Herschel observations of embedded protostellar clusters in the Rosette molecular cloud

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1. Introduction

The HOBYS Herschel (Pilbratt et al. 2010) imaging survey (Motte et al. 2010) is a key programme for studying the sites of OB star formation within a distance of 3 kpc. The parallel mode scan observations, carried out with the PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010; Swinyard et al. 2010) instruments, provide maps of massive cloud complexes in the wavelength range of 70 to 500 μm, and thus a census of the different stages of star formation from prestellar cores to evolved young stellar objects (YSOs). As an excellent example of a massive cloud complex associated with — and under the influence of — an OB star cluster (NGC 2244), the Rosette molecular cloud was observed for HOBYS during the Herschel science demonstration phase (Motte et al. 2010). The influence of NGC 2244 on the cloud complex is discussed in the accompanying paper by Schneider et al. (2010), while Di Francesco et al. (2010) assesses the clump population. For consistency with Schneider et al. (2010), the distance of Rosette adopted here is 1.6 kpc. Many previous studies have targeted the Rosette complex. Ongoing star formation across the molecular cloud is traced by the presence of several luminous IRAS sources that are associated with massive clumps seen in CO emission (Cox et al. 1990; Williams et al. 1995; Schneider et al. 1998). Towards these dense regions, the embedded clusters PL1 to PL7 have been identified by Phelps & Lada (1997) from near-infrared observations. The list of clusters in Rosette was extended by Li & Smith (2005), Román-Zúñiga et al. (2008), and Poulton et al. (2008) using near-infrared and Spitzer observations.

In this paper, we make use of the unprecedented spatial resolution and sensitivity of Herschel to establish a sample of compact far-infrared sources that represent prestellar objects and to determine their fundamental properties (luminosities and envelope masses) from their spectral energy distribution (SED). In the early phases of the collapse of a prestellar core and the initial accretion of matter onto a central protostar, the SED of a Class 0 source is dominated by thermal emission from cold dust in the envelope ($M_{\text{env}} > M_*$, André et al. 2000). The SED of a more evolved Class I source is shifted to mid-infrared wavelengths, indicating a comparatively less massive, hotter envelope ($M_{\text{env}} < M_*$). To investigate the evolutionary stage,
the protostellar envelope mass is usually compared to the bolometric luminosity, which serves as a proxy for stellar mass. The Herschel observations for the first time cover the peak of the protostellar SED thus constraining the evolutionary stage of early-to-evolved YSOs. This overcomes the previous difficulties distinguishing Class 0 and Class I sources using near- to mid-infrared data.

2. Observations
The Rosette molecular cloud was observed by Herschel on October 20, 2009 in the parallel scan map mode (scanning speed of 20″/sec) simultaneously with SPIRE at 250/350/500 μm and PACS at 70/160 μm. Two perpendicular scans (consisting of parallel scanlegs interspersed by turn-arounds) were taken to cover a SPIRE/PACS common area of 1° × 1°. The data are reduced with scripts developed in HIPE\(^1\) (Ott 2010, version 2.0 for SPIRE and version 3.0 for PACS). The PACS data are deglitched from cosmic ray second-level data and then high-pass filtered with a scanleg filter width to preserve the extended emission up to the map size scale. The combined scans are finally projected using the HIPE MadMAP implementation with the noise table Invntt version 1. For details of the SPIRE data reduction, see Schneider et al. (2010). The maps are flux-calibrated according to the correction factors of Swinyard et al. (2010) and Poglitsch et al. (2010), compared to 2MASS to correct for a ~6″ pointing offset and a systematic offset of ~4″ between SPIRE and PACS. The entire set of Herschel maps is shown in Motte et al. (2010), and Fig. 4 (available online) shows the 70 and 160 μm maps.

3. Results and analysis
Rosette harbours several luminous far-infrared sources that represent candidate high-mass protostars with AFGL 961 being the brightest (see Motte et al. 2010). In their vicinity, the Herschel 70 and 160 μm maps reveal a population of compact sources that likely represent YSOs of low to intermediate mass. The most prominent cluster is the one towards the Rosette molecular cloud centre (see Fig. 1). The emission traces heated protostellar envelope material; in contrast, starless cores are not expected to be detected as compact sources at 70 μm. That Herschel resolves individual protostars, even though the Rosette region lies at an intermediate distance, allows us to study the physical properties of the protostar population based on unprecedented far-infrared data.

3.1. Identification of compact protostellar sources
To identify the positions of the compact Herschel protostars, we made use of the 70 μm MRE-GCL catalogue (Motte et al. 2010) derived using the method of Motte et al. (2007). Spatial scales larger than 0.5 pc were filtered out using MRE (Starck & Murtaugh 2006), and the Gaussclumps programme applied (Kramer et al. 1998). We focus on the protostellar objects clearly detected at 70 μm with FWHM < 15″ and derived the 70 and 160 μm flux measurements using aperture photometry. Sources that are faint or that appear non-singular, either of which prevents a useful measurement, were excluded. The aperture diameters were chosen to correspond to a physical scale of 0.1 pc (corresponding to a source FWHM size of roughly 0.05 pc) and the background is determined in adjacent annuli. Figures 1 and 3 show that protostars are resolved at 70 and 160 μm but blend together in the submillimetre, preventing a dust temperature measurement on the protostar scale. Thus we adopted temperatures determined by Motte et al. (2010) derived from the integrated emission on larger scales, using greybody fits with a dust emissivity index of β = 2 and assuming \( T_d = 20 \) K for sources where no estimate is available. This may introduce a bias towards lower temperatures as the protostellar envelopes are expected to be warmer than their surroundings. The envelope masses were estimated by scaling the greybody curve (of dense cores) to the 160 μm fluxes (of protostellar envelopes). Eighty eight protostars are the basis for the further study described below. Due to the compactness criterion, this sample does not include the high-luminosity, high-mass protostellar objects (e.g. AFGL 961).

Partly based on Spitzer IRAC and MIPS data of the same region obtained by Poulton et al. (2008) and on 2MASS, a catalogue supplied by Balog et al. (in prep. hereafter referred to as Spitzer catalogue) was used to search for source counterparts in the near- and mid-infrared. Considering ~1900 sources catalogued at 24 μm, 17 Herschel sources have no counterpart. The inspection of the maps shows that most of them are either not covered by the MIPS observations or are not included in the catalogue owing to artifacts in the Spitzer maps. Interestingly, 5 sources have only been detected with Herschel but not at 24 μm (completeness limit ~0.5 mJy). The Spitzer catalogue also includes a classification of source type using the IRAC colours Gutermuth et al. (2008). The compiled flux measurements that include the Spitzer catalogue are used to estimate bolometric luminosities by integration over the SEDs, where we use the submillimetre fluxes of a greybody with the adopted dust temperature. The current lack of resolved submillimetre flux measurements means that the mass derivation relies on assumptions of the dust temperature and emissivity, and we estimate that the relative accuracy is roughly a factor of 2, and similarly for the luminosities. This will be improved by forthcoming studies.

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\(^1\) HIPE is a joint development by the Herschel Science Ground Segment Consortium, consisting of ESA, the NASA Herschel Science Center, and the HIFI, PACS, and SPIRE consortia.
3.2. Evolutionary stage of the Herschel protostars in Rosette

The derived envelope masses and bolometric luminosities are plotted in an evolutionary diagram shown in Fig. 2. For clarity, we omit the aforementioned error estimates. Such a diagram is proposed to trace the evolution of embedded protostars (Bontemps et al. 1996; Saraceno et al. 1996) because Class 0 sources display relatively high envelope masses that decrease during the mass accretion, while the luminosities (protostellar core and accretion) increase significantly. Evolutionary tracks are displayed for stars of different masses (cf. André et al. 2008; Bontemps et al. 2010). The Rosette protostar sample occupies the low- to high-mass regimes in the diagram. Compared to findings in the nearby Aquila star-forming region (Bontemps et al. 2010), the Rosette protostars are comprised of higher masses. The diagonal lines in Fig. 2 (see caption) indicate an approximate border zone between envelope-dominated Class 0 and star-dominated Class I objects based on the comparison of $M_{env}$ to $M_*$ (cf. André & Montmerle 1994).

A surprisingly large fraction of our sample (~2/3) falls into the candidate Class 0 regime above these lines. A practical criterion inferred from this diagram is $L_\lambda > 350 \mu m/L_{bol} > 1%$ for Class 0 (André et al. 2000). In Fig. 2, we apply this criterion obtained from the previously compiled SEDs. It results in more intermediate-mass objects being classified as Class I, i.e., a more conservative Class 0 assignment that we hereafter refer to as “candidate Class 0”. The classification of objects lying near the border zone remains tentative because of the uncertainty in converting the $M_{env}/M_*$ ratio into measurable quantities. In particular, the Herschel photometry of nearby protostars will reduce this uncertainty, after data from several regions have been analysed. Until a detailed analysis of the completeness is available, our finding thus remains preliminary. Nevertheless, it indicates that Herschel allows us to significantly extend the sample of known Class 0 objects.

Seven protostar subsamples are established according to their location (field denominations in Schneider et al. 2010), which are listed in Table 1. The distributed protostars contain sources located towards the tip of pillar structures (Schneider et al. 2010). Each subsample spans a wide mass range from 0.1 to about 10 $M_\odot$. In Fig. 2 the central cluster and PL7 subsamples are emphasised by coloured symbols. In the 2 to 10 $M_\odot$ range, the central cluster harbours a significant number of sources in the Class 0 regime with 4 to 30 $L_\odot$. Also the PL7 cluster contains 3 sources with relatively low luminosities. This indicates that both the central cluster and the PL7 cluster are younger compared to the remaining protostars.

3.3. The classification of protostars in the central cluster

Among the 27 Herschel protostars in our central cluster sample, the Spitzer classification (see Sect. 3.1) gives 12 Class I objects and one for Class II. For PL7, 5 out of 11 sources are classified as Class I. These classifications are added to the symbols in Fig. 2 as “I” and “II”, for comparison to their location in the evolutionary diagram and the distinction by the $L_\lambda > 350 \mu m/L_{bol}$ ratio. Notably, about half of the sources seen as Class I by Spitzer in these two subsamples correspond to sources with $L_\lambda > 350 \mu m/L_{bol} > 1%$ and thus represent candidate Class 0 protostars. They are intermixed with the unclassified sources in the diagram that lack detections in one or several bands. This suggests that the classification based on the near- to mid-infrared data alone has to be partly revised in light of the Herschel measurement of the protostellar envelope.

To overcome incompleteness in our Herschel catalogue and to provide a first census of how many sources classified using near- to mid-infrared data are affected, we have focused on the central cluster. We redefined the cluster area as a rectangular field towards the Rosette molecular cloud centre and selected a total of 86 catalogued 24$\mu$m sources in that field. Three 24$\mu$m sources were classified as probably extragalactic and are excluded. We then inspected the Herschel 70$\mu$m map for counterparts. The field and the resulting detection statistics are given in Table 2. The chosen field excludes PL4 and its vicinity because the extended emission there makes source identification very uncertain. Still there is a bias towards bright objects, and we estimate an uncertainty of three sources in total and one source per subsample. Based on visual inspection, we find a 70$\mu$m detection rate of about 50% for YSOs seen at 24$\mu$m.

Table 1. Protopstar subsamples seen by Herschel in Rosette.

<table>
<thead>
<tr>
<th>Region</th>
<th>Associated Clusters</th>
<th># Protopstars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre</td>
<td>PL4/5, REF/L08, E</td>
<td>27</td>
</tr>
<tr>
<td>Shell</td>
<td>PL1, A</td>
<td>5</td>
</tr>
<tr>
<td>Monoceros Ridge/</td>
<td>Extended Ridge</td>
<td>11</td>
</tr>
<tr>
<td>PL3</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>AFGL 961</td>
<td>PL6</td>
<td>6</td>
</tr>
<tr>
<td>PL7</td>
<td>G</td>
<td>11</td>
</tr>
<tr>
<td>Distributed</td>
<td>–</td>
<td>24</td>
</tr>
</tbody>
</table>


Table 2. Classification of protostars in the Rosette central cluster.

<table>
<thead>
<tr>
<th></th>
<th># total</th>
<th># Class II</th>
<th># Class I</th>
<th># Unclass.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible in 70$\mu$m</td>
<td>40 (±3)</td>
<td>10 (±1)</td>
<td>19 (±1)</td>
<td>11 (±1)</td>
</tr>
<tr>
<td>In Herschel sample</td>
<td>22</td>
<td>1</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Candidate Class 0</td>
<td>14</td>
<td>0</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

Notes. The cluster area is defined here by 98.5° < RA < 98.6° and 4.25° < Dec < 4.4°. The table head classifications are based on near- to mid-infrared measurements. Class 0 candidates exhibit $L_\lambda > 350 \mu m/L_{bol} > 1%$. Table 1 provides a first census of how many sources classified using near- to mid-infrared data are affected, we have focused on the central cluster. We redefined the cluster area as a rectangular field towards the Rosette molecular cloud centre and selected a total of 86 catalogued 24$\mu$m sources in that field. Three 24$\mu$m sources were classified as probably extragalactic and are excluded. We then inspected the Herschel 70$\mu$m map for counterparts. The field and the resulting detection statistics are given in Table 2. The chosen field excludes PL4 and its vicinity because the extended emission there makes source identification very uncertain. Still there is a bias towards bright objects, and we estimate an uncertainty of three sources in total and one source per subsample. Based on visual inspection, we find a 70$\mu$m detection rate of about 50% for YSOs seen at 24$\mu$m.
et al. (2010) derive a dust temperature of 15 K. We focus on Herschel dense core revealed by cal basis is low and will be improved in forthcoming studies.

About 25% of 26 previously classified Class I sources, which indicates that many of the latter are Class 0 candidates. This applies to 7 out of 18 unclassified sources in the central cluster at 24, 70, 160, and 250 μm and their spectral energy distributions.

Due to their rising SED, we expect more 70 μm detections for Class I than for Class II, and find about 3/4 compared to about 1/4. In the second row of Table 2, we list the corresponding numbers for the analysed Herschel sample and the classification for the same field. Roughly, we include about half of the visible 70 μm sources in the Herschel list. About 2/3 of these are Class 0 candidates. This applies to 7 out of 18 unclassified sources, which indicates that many of the latter are Class 0 protostars. About 25% of 26 previously classified Class I sources are also Class 0 candidates, possibly more. Notably, our statistical basis is low and will be improved in forthcoming studies.

For illustration, we consider a particularly interesting large dense core revealed by Herschel which is resolved into several protostars at 70/160 μm (Fig. 3). For the whole core, Motte et al. (2010) derive a dust temperature of 15 K. We focus on 4 sources clearly detected at 70 μm labelled 1 to 4 from west to east. The projected separation between two neighbours is around 0.14 pc. At 24 μm, only sources 1 to 3 are detected with decreasing brightness. Based on the Spitzer data, source 1 is classified as Class I, while the others remain unclassified owing to non-detection in one or more of the IRAC bands (sources 2 and 3) or non-detection in all near- to mid-infrared bands (source 4). At 70 and 160 μm source 4 shows up and the adjacent source 3 is the brightest of the group. The SED slopes (Fig. 3) between 8 and 70 μm for sources 1, 2, and 3 become increasingly steep. Beyond 70 μm they are shallower, and the 160 to 70 μm flux ratio is the highest for source 4. The mid- to far-infrared colours allow us to distinguish the source evolutionary stages.

The derived luminosities ($M_{\text{env}}^{<0.05}$, $L_{\text{bol}} > 350 \mu$m/(100 km/s)) are $15 L_{\odot}$ (2 $M_{\odot}$, 1%) for source 1, $8 L_{\odot}$ (3 $M_{\odot}$, 3%) for source 2, $8 L_{\odot}$ (5 $M_{\odot}$, 4%) for source 3, and $5 L_{\odot}$ (4 $M_{\odot}$, 6%) for source 4. We note that the assumption of a single dust temperature means the relative mass differences are not well constrained. Relatively similar in mass, the sources represent successive evolutionary stages from early Class 0 (source 4) to “flat-spectrum” Class I (source 1). This is a first example of how Herschel resolves the early evolution of protostars in combination with Spitzer measurements.

4. Implications

This initial study of the protostellar population in Rosette using the HOBYS observations already shows that Herschel provides detailed insight into the earliest stages of the protostellar evolution at low to high masses, and in particular identifies thus far elusive Class 0 objects. The now available Herschel photometry will be the basis for establishing firm criteria (mid- to far-infrared colours) for distinguishing the evolutionary stages, including the observations of nearby regions where individual (low-mass) protostars are resolved in the submillimetre. Based on a complete protostar catalogue of the Rosette complex, we will examine the evolution of the star formation activity over the whole cloud also with respect to triggering (cf. Schneider et al. 2010).

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**Fig. 4.** HOBYS Herschel 70 and 160 μm maps of the Rosette molecular cloud (flux unit: MJy/sr). See Motte et al. (2010) for details on the sensitivity of the entire Herschel data set.

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