Herschel observations of embedded protostellar clusters in the Rosette molecular cloud


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Herschel* observations of embedded protostellar clusters in the Rosette molecular cloud**


(Affiliations are available in the online edition)

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Abstract

The Herschel OB young stellar objects survey (HOBYS) has observed the Rosette molecular cloud, providing an unprecedented view of its star formation activity. These new far-infrared data reveal a population of compact young stellar objects whose physical properties we aim to characterise. We compiled a sample of protostars and their spectral energy distributions that covers the near-infrared to submillimetre wavelength range. These were used to constrain key properties in the protostellar evolution, bolometric luminosity, and envelope mass and to build an evolutionary diagram. Several clusters are distinguished including the cloud centre, the embedded clusters in the vicinity of luminous infrared sources, and the interaction region. The analysed protostellar population in Rosette ranges from 0.1 to about 15 \( M_\odot \), with luminosities between 1 and 150 \( L_\odot \), which extends the evolutionary diagram from low-mass protostars into the high-mass regime. Some sources lack counterparts at near- to mid-infrared wavelengths, indicating extreme youth. The central cluster and the Phelps & Lada 7 cluster appear less evolved than the remainder of the analysed protostellar population. For the central cluster, we find indications that about 25\% of the protostars classified as Class I from near- to mid-infrared observations of embedded protostellar clusters (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 protostellar 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 protostellar 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 (\( M_{\text{env}} > M_\star \), 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 (\( M_{\text{env}} < M_\star \)). 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 250/350/500μm and PACS at 70/160μm. 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 de-glitched from cosmic ray impacts with the HIPE second-level method 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 Inviqt 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 160μm 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 160μm 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 70μm. 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 70μm 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 & Murtagh 2006), and the Gaussclumps programme applied (Kramer et al. 1998). We focused on the protostellar objects clearly detected at 70μm with FWHM < 15″ and derived the 70 and 160μm 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 160μm 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 low 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 160μm 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 24μm, 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 24μm (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.

\(^1\) 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.

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Fig. 1. PACS 70μm of the Rosette molecular cloud centre. The region harbours the embedded clusters PL4 (northwest), PL5 (southeast), and a concentration of compact Herschel sources.
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 protostellar envelopes are plotted in an evolutionary diagram shown in Fig. 2. The derived envelope masses and bolometric luminosities are inferred from this diagram is the classification very uncertain. Still there is a bias towards bright objects. The cluster area is defined here by 98.5° < RA < 98.6° and 4.25° < Dec < 4.4°. The table head classifications given in Table 2. The chosen field excludes PL4 and its surroundings. The table and the resulting detection statistics are derived from the central cluster (cf. Andrè & 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 between envelope-dominated Class 0 and star-dominated Class I objects based on the comparison of $M_{env}$ to $M_*$ (cf. Andrè & Montmerle 1994).

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.

### Table 1. Protostar subsamples seen by Herschel in Rosette.

<table>
<thead>
<tr>
<th>Region</th>
<th>Associated Clusters</th>
<th># Protostars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre</td>
<td>PL4/5, REFL08, E</td>
<td>27</td>
</tr>
<tr>
<td>Shell</td>
<td>PL1, A</td>
<td>5</td>
</tr>
<tr>
<td>Monoceros Ridge/Extended Ridge</td>
<td>PL2, C</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>

Notes. Cluster names are PL for Phelps & Lada (1997), REFL for Roman-Zuluaga et al. (2008), A...G for Poulon et al. (2008).

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

<table>
<thead>
<tr>
<th>24 µm sources</th>
<th>Total</th>
<th>Class 0</th>
<th>Class I</th>
<th>Class II</th>
<th>Unclass.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible in 70 µm</td>
<td>83</td>
<td>10 (±1)</td>
<td>26 (±1)</td>
<td>11 (±1)</td>
<td>9</td>
</tr>
<tr>
<td>In Herschel sample</td>
<td>22</td>
<td>1</td>
<td>12</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Candidate Class 0</td>
<td>14</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Notes. The cluster area is defined by $98.5° < RA < 98.6°$ and $4.25° < Dec < 4.4°$. The table head classifications are added to the symbols in Fig. 2 as “I” and “II”, for comparison to their locations in the central cluster and PL7 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 nearest 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 µm sources in that field. Three 24 µm sources were classified as probably extragalactic and are excluded. We then inspected the Herschel 70 µm 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 µm detection rate of about 50% for YSOs seen at 24 µm.
et al. (2010) derive a dust temperature of 15 K. We focus on
1 dense core revealed by
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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References
André, P., et al. 2000, Protostars and Planets IV, 59

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 and their spectral energy distributions.

The derived luminosities (L_{env} < 0.5 × 10^5 L_{⊙}, L_{bol} > 350 μm/L_{bol}) are 15 L_{⊙} (2 M_{⊙}, 1%) for source 1, 8 L_{⊙} (3 M_{⊙}, 3%) for source 2, 8 L_{⊙} (5 M_{⊙}, 4%) for source 3, and 5 L_{⊙} (4 M_{⊙}, 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.

Fig. 3. Four protostars in the central cluster at 24, 70, 160, and 250 μm and their spectral energy distributions.
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.