Herschel observations of embedded protostellar clusters in the Rosette molecular cloud


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Letter to the Editor

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(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☉ with luminosities between 1 and 150 L☉, 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 data are actually candidate Class 0 objects. As a showcase for protostellar evolution, we analysed four protostars of low- to intermediate-mass in a single dense core, and they represent different evolutionary stages from Class 0 to Class I. Their mid- to far-infrared spectral slopes flatten towards the Class I stage, and the 160 to 70 μm flux ratio is greatest for the presumed Class 0 source. This shows that the Herschel observations characterise the earliest stages of protostellar evolution in detail.

Key words. stars: formation – stars: protostars – ISM: individual objects: Rosette

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 map 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 protostellar objects and 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 (Menv > 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 (Menv < 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 250/350/500μm 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 deglitched 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 Invnt 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 & Murtaugh 2006), and the Gaussclumps programme applied (Kramer et al. 1998). We focus 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

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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.
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. They are intermixed with the unclassified sources in the diagram that lack detections in one or several bands. This 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 a counterpart. 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 about five 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. 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/</td>
<td>Extended Ridge</td>
<td></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 Román-Zúñiga et al. (2008), A...G for Poulton et al. (2008).

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

<table>
<thead>
<tr>
<th>24\mu m sources</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>
</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 based on near- to mid-infrared measurements. Class 0 candidates exhibit $L_\lambda/350\mu m/L_{bol}$ > 1%.
et al. (2010) derive a dust temperature of 15 K. We focus on 1eral protostars at 70 μm. All the cores resolved in one or more of the IRAC bands are also Class 0 candidates, possibly more. Notably, our statistical analysis indicates that many of the latter are Class 0 protostars. About 25% of 26 previously classified Class I sources are Class 0 candidates. This applies to 7 out of 18 unclassified and 4 sources clearly detected at 70 μm. The SED slopes (Fig. 3) between 8 and 70 μm 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 \( L_{\text{bol}} / M_\odot \) are 15 \( L_\odot \) (2 \( M_\odot \), 1%) for source 1, 8 \( L_\odot \) (3 \( M_\odot \), 3%) for source 2, and 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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References


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.