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INITIAL HIGHLIGHTS OF THE HERSCHEL IMAGING SURVEY OF OB YOUNG STELLAR OBJECTS (HOBYS)

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Abstract. We present initial Herschel HOBYS highlights of the Rosette molecular complex. The five Herschel wavebands of SPIRE (250/350/500 μm) and PACS (70 and 160 μm) allows HOBYS to provide an unbiased and complete census of intermediate- to high-mass young stellar objects, some of which are not detected by Spitzer. Key core properties, derived from spectral energy distributions, such as bolometric luminosity and mass, are used to constrain their evolutionary status.

Keywords: stars: formation, stars: early-type, submillimetre continuum, Herschel, protostars, ISM: individual (Rosette)

1 High-mass star formation and HOBYS

Our knowledge of high-mass star formation ($> 8\,\mathrm{M}_{\odot}$) is still rather schematic, though an evolutionary sequence of their earliest phases is staring to emerge. Bright IRAS sources embedded within massive envelopes have been recognised as high-mass protostellar objects (e.g. Beuther et al. 2002). Cold massive dense cores associated with weak mid-infrared emission, but with clear signposts of OB-type protostars, have been qualified as IR-quiet and are observed to host high-mass Class-0 protostars (Motte et al. 2007; Bontemps et al. 2010). Controversy remains regarding the existence and lifetime of high-mass analogues of prestellar cores, since infrared dark clouds are numerous (Simon et al. 2006) but only a few harbour starless, massive, and dense enough cores (e.g. Motte et al. 2007).

The Herschel imaging survey of OB Young Stellar objects (HOBYS, see `http://hobys-herschel.cea.fr`) is a guaranteed time key program which aims to identify and characterise the precursors of OB stars, measure the core/envelope mass and bolometric luminosity and assess the importance of triggering in high-mass star forming regions. Using the SPIRE/PACS instruments, HOBYS will image all of the molecular complexes forming OB-type stars at distances less than 3 kpc from the Sun. These 70–500 μm observations provide an unbiased census of massive young stellar objects (YSOs) and trace the large-scale emission of the surrounding clouds. This survey will yield, for the first time, accurate bolometric luminosity and envelope mass estimates for homogeneous and complete samples of OB-type YSOs, allowing us to estimate the evolutionary state of each source, and the lifetime of each evolutionary state.

We present here some of the first results from HOBYS focusing on the Rosette molecular cloud (Motte et al. 2010; Schneider et al. 2010; Hennemann et al. 2010). For a review of the Rosette see Schneider et al. (2010).

2 Observations

The Rosette molecular cloud was observed on October 20, 2009, during the science demonstration phase, using the parallel PACS/SPIRE mode at 70/160μm and 250/350/500μm, respectively, and a scan speed of 20”/s. The data reduction for the PACS and SPIRE observations are as described in Hennemann et al. (2010) and Schneider et al. (2010), respectively.

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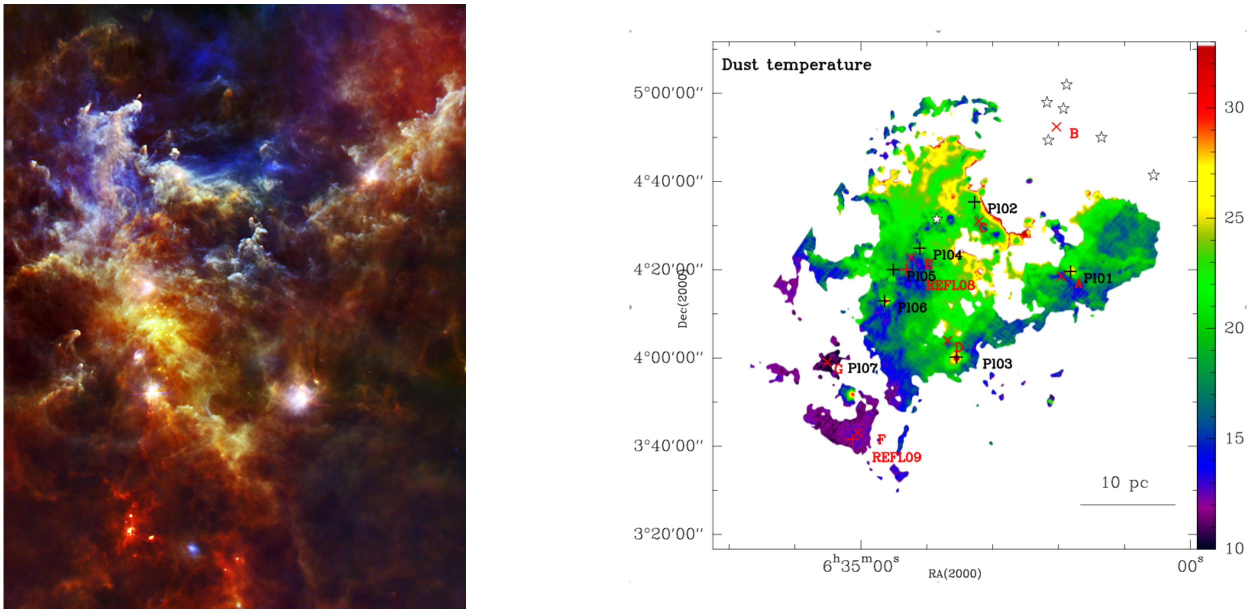

Fig. 1. bf Left: Composite 3-colour Herschel image of the Rosette molecular complex. PACS 70μm (blue), PACS 160μm (green), and SPIRE 250μm (red) (Motte et al. 2010). **Right**: Dust-temperature map obtained from a pixel-by-pixel SED fit to the five Herschel wavebands. Black crosses, and 'PL' indicate clusters identified by Phe & Lada (1997) while red crosses and labels are clusters from Poulton et al. (2008), and label REFL the clusters from Román-Zúñiga et al. (2008) (see Schneider et al. 2010, for more detail).

3 Results

Figure 1 (left), presents a three-colour image of the Rosette molecular complex. The sensitivity achieved in this image allows detection of compact YSOs down to 5-$\sigma \simeq 0.3\,M_{\odot}$ at 160 μm. In Rosette, this corresponds to spatial scales ranging from $\sim$0.05–0.2 pc to $\sim$40 pc.

The HII-region/molecular cloud interface, where the UV radiation has the largest impact is the most prominent in the blue and shows the most complex and filamentary structure (see Fig, 1, left). The dust temperature map, obtained from a pixel-to-pixel SED fit to the five Herschel wavebands (Fig. 1, right), shows that the highest temperatures in this complex (30 K) are found at this interface. At this point, the UV radiation from the NGC 2244 cluster has erased the low-density gas, leaving only the densest gas as 'pillars'. Schneider et al. (2010) show that the penetration depth of this radiation is $\sim$ 10 pc, which is approximately the border between the warm and colder gas phase. At larger depths, the cold, dense molecular ridge is less influenced by the UV radiation and appears to be less structured. The dust temperature map shows a decreasing temperature with increasing distance from the interface, such that the coldest region is in the remote part of the cloud. The total mass of the Rosette complex mapped by Herschel is $\sim$105 $M_{\odot}$. The column density map (Fig. 5 Schneider et al. 2010) indicates a clear increasing gradient in average density from the HII-region into the molecular cloud. In the 'compression' zone of the molecular cloud/HII-region interface, the densities are around 0.5×10^3 cm^3, whilst the remote regions have a higher densities of 1.8×10^3 cm^3 and 3.9×10^3 cm^3, respectively.

Source extraction was performed using a multi-resolution analysis (Motte et al. 2007), which filters out large spatial scales (>0.5 pc) in order to focus on compact sources. Above 5-σ, we extract 4000 – 900 sources at 70 and 500 μm, respectively (see Motte et al. 2010, for more detail). Analysis of Rosette yields a catalogue of dense cores with sizes 0.02-0.3 pc at 160 μm.

Simple grey-body spectral energy distributions (SEDs) were drawn for the 46 most massive cores, by combining these Herschel observations with Spitzer MIPS and IRAC fluxes where possible. For each core, the dust temperature and the mass were obtained, which vary from 12-40 K and 0.8-39 $M_{\odot}$, for the sample (Motte et al. 2010). The bolometric luminosity of each massive dense core was estimated from integration of the SED over the 3.6-500 μm range. The protostellar or starless nature of the dense cores was drawn from associations with or without 24μm Spitzer emission, respectively.

Six protostellar and three prestellar cores with radii $\sim$0.18 pc and masses between $\sim$20-40 $M_{\odot}$ were identified from SED fitting (Motte et al. 2010). Four of the six protostars are cooler and have lower luminosities which makes them good candidates for hosting early stage, high-mass protostars. The three massive starless cores are slightly larger and more massive than the protostellar sample ($\sim$0.22 pc, $\sim$30 $M_\odot$) and are also cooler (13 K). They are likely gravitationally bound and are possible examples of high-mass analogues of low mass prestellar cores (Motte et al. 2010).

A handful of starless dense cores were also discovered to have warm temperatures: $\sim$19 $M_\odot$, $\sim$0.14 pc, $\sim$27 K (see Fig. 5a Motte et al. 2010). The nature of these objects is as yet unclear, but they do not seem to correspond to remnant cloud surrounding an already formed cluster. If gravitationally bound, these warm, massive, but not centrally peaked, dense cores could concentrate their mass, cool down, and then form the next generation of intermediate- to high-mass stars in Rosette. They have high luminosities ($\sim$100 $L_\odot$) and are part of the $>10^3$ $L_\odot$ IRAS point sources associated with the PL1, PL3, and PL4 embedded clusters (see Fig. 1, right).

Herschel traces younger, colder objects (cf. Fig. 3, core 3) compared with Spitzer (core 1). In the submillimetre, i.e. 250μm, the sources are blended together preventing a dust temperature measurement on the protostar scale. Thus, in order to profile early-stage protostars it is necessary to concentrate on the 70 and 160 μm Herschel data (Hennemann et al. 2010).

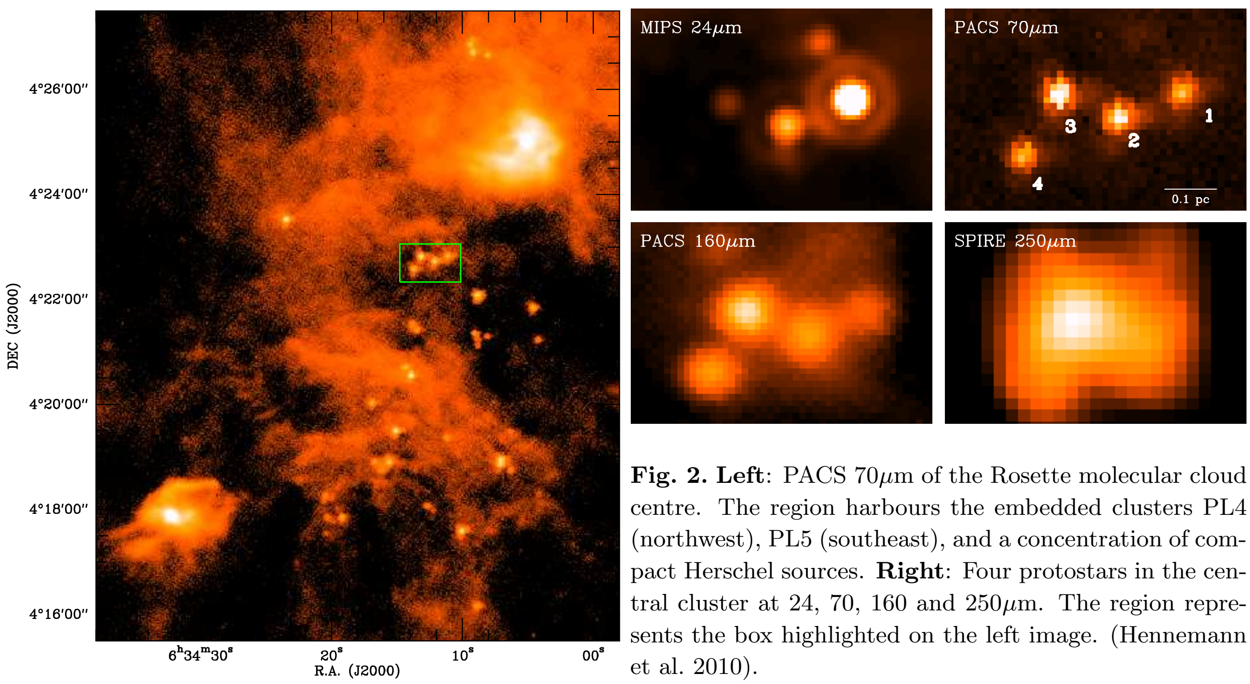

Fig. 2. Left: PACS 70μm of the Rosette molecular cloud centre. The region harbours the embedded clusters PL4 (northwest), PL5 (southeast), and a concentration of compact Herschel sources. **Right**: Four protostars in the central cluster at 24, 70, 160 and 250μm. The region represents the box highlighted on the left image. (Hennemann et al. 2010).

Hennemann et al. (2010) extracted a sample of 88 protostars from the aforementioned Motte et al. (2010) catalogue which were clearly detected at 70μm with FWHM <15". 17 of these sources are devoid of 2MASS and Spitzer associations. Using 70 and 160μm fluxes derived from aperture photometry, in addition to Spitzer data when available, and assuming the same dust temperatures as derived from Motte et al. (2010), SEDs were drawn to estimate the bolometric luminosity and envelope masses of these 88 protostellar objects.

Figure 3 plots the bolometric luminosity as a function of the envelope mass. This relation is often used as a proxy for stellar mass and evolution (cf André et al. 2000; Bonte et al. 1996). Evolutionary tracks are displayed for stars of different masses (cf. André et al. 2008; Bontemps et al. 2010). The Rosette protostellar sample of occupies the low- to high-mass regimes in the diagram. The diagonal lines in Fig. 3 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. Andre & Montmerle 1994).

A surprisingly large fraction of the protostellar sample ($\sim$2/3) falls within the candidate Class 0 regime (top left part of the diagram). A practical criterion inferred from this diagram is $L_\lambda > 350\,\mu m/L_{bol} > 1\%$ for Class 0 sources (André et al. 2000). Applying this relation to this protostellar sample results in more intermediate-mass objects classified as Class I, i.e., a more conservative Class 0 assignment, i.e, 'Candidate Class 0'. The central cluster harbours a significant number of sources in the Class 0 regime between 2–10 $M_\odot$ and 4–30 $L_\odot$, whilst the PL7 region (see Fig. 1) contains 3 sources with relatively low luminosities, indicating that both regions are younger compared with the remaining protostars in the sample.

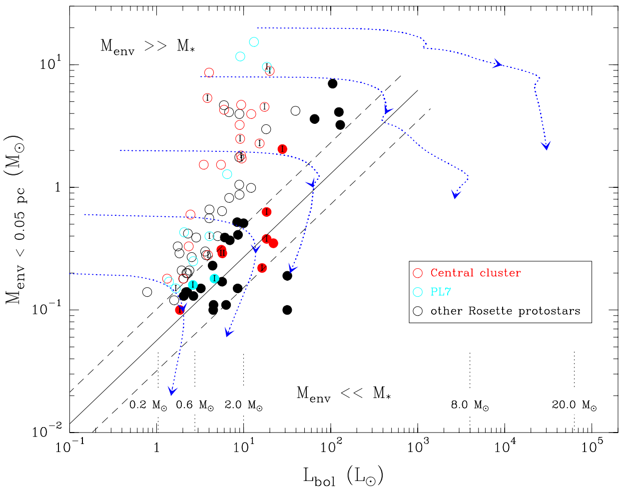

Fig. 3. Envelope mass versus bolometric luminosity diagram for the sample of Herschel protostars in Rosette. The central cluster and PL7 subsamples are emphasised by coloured symbols. Evolutionary tracks for stellar masses between 0.2 and 20 $M_\odot$ are included. The solid line corresponds to 50% of the mass accreted; the dashed lines account for the estimated uncertainties of M_{env} and L_{bol}. Open symbols: candidate Class 0 protostars with $L_\lambda > 350\,\mu m/L_{bol} > 1\%$; filled symbols: Class I protostars with $L_\lambda > 350\,\mu m L_{bol} \leq 1\%$ (Hennemann et al. 2010).

4 Conclusions

The initial results from the HOBYS key program are promising as Herschel provides detailed insight into the workings of the Rosette molecular cloud. In particular, there is: a clear dust tempereature and tentative age gradient running from the HII-region/cloud interface into the cloud (Schneider et al. 2010); three massive prestellar dense cores and a few warm starless cores that could represent the highly-sough precursors of high mass protostars (Motte et al. 2010); and rich protoclusters forming low- to high-mass protostars, among which there are a large number of Class 0 protostars (Hennemann et al. 2010).

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