The ATLASGAL survey: a catalog of dust condensations in the Galactic plane

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ABSTRACT

Context. The formation processes and the evolutionary stages of high-mass stars are poorly understood compared to low-mass stars. Large-scale surveys are needed to provide an unbiased census of high column density sites which can potentially host precursors to high-mass stars.

Aims. The ATLASGAL survey covers 420 sq. degree of the Galactic plane, between −80° < ℓ < +60° at 870 μm. Here we identify the population of embedded sources throughout the inner Galaxy. With this catalog we first investigate the general statistical properties of dust condensations in terms of their observed parameters, such as flux density and angular size. Then using mid-IR surveys we aim to investigate their star-formation activity and the Galactic distribution of star-forming and quiescent clumps. Our ultimate goal is to determine the statistical properties of quiescent and star-forming clumps within the Galaxy and to constrain the star-formation processes.

Methods. We optimized the source extraction method, referred to as MRE-GCL, for the ATLASGAL maps in order to generate a catalog of compact sources. This technique is based on a multi-scale filtering to remove extended emission from clouds to better determine the parameters corresponding to the embedded compact sources. In a second step we extract the sources by fitting 2D Gaussians with the Gaussclumps algorithm.

Results. We have identified in total 10861 compact sub-millimeter sources with fluxes above 5σ. Completeness tests show that this catalogue is 97% complete above 5σ and > 99% complete above 7σ. Correlating this sample of clumps with mid-infrared point source catalogues (MSX at 21.3 μm and WISE at 22 μm) we have determined a lower limit of 33% that are associated with embedded protostellar objects. We note that the proportion of clumps associated with mid-infrared sources increases with increasing flux density, achieving a rather constant fraction of ≈75% of all clumps with fluxes over 5Jy/beam being associated with star-formation. Examining the source counts as a function of Galactic longitude we are able to identify the most prominent star forming regions in the Galaxy.

Conclusions. We present here the compact source catalog of the full ATLASGAL survey and investigate their characteristic properties. From the fraction of the likely massive quiescent clumps (~25%) we estimate a formation time-scale of ≈ 7.5 ± 2.5 × 10⁵ yr for the deeply embedded phase before the emergence of luminous YSOs. Such a short duration for the formation of high-mass stars in massive clumps clearly proves that the earliest phases have to be dynamic with supersonic motions.

Key words. surveys – star formation – massive stars – ISM: structure – Galaxy: structure

1. Introduction

1.1. High-mass star-formation in the Galactic plane

The dominant formation mechanism leading to the birth of high-mass stars is still an enigma in modern astrophysics. Unlike for low-mass stars, there is no clear, observationally constrained evolutionary sequence for individual protostars above 10 M☉. This is due to the fact that they are rare and likely evolve on short time-scales, therefore it is challenging to identify and study them. Yet, they are fundamental building blocks of galaxies, they provide significant mechanical and radiative feedback to the interstellar medium and enrich it with heavy elements. They are used as a tool to study star-formation and the evolution of galaxies in various environments as a function of redshift (Kennicutt 1998), it is therefore crucial to study them first locally, in our Galaxy in much greater detail.

Observations of high-mass stars are greatly hindered by the fact that they are still deeply embedded in their dust cocoons when reaching the main sequence. Since star-formation in general proceeds in the densest regions of molecular clouds, dust is the best tracer to identify these locations (see Evans 1999 for a review). In fact the first systematic surveys for massive
young stellar objects (MYSOs) have used the infrared emission of heated dust to pin down the most luminous sites in our Galaxy. These studies used the IRAS survey (Hughes & MacLeod 1985; Wood & Churchwell 1989; Bronfman et al. 1996; Molinari et al. 1996) to look for H II regions and MYSOs (Sridharan et al. 2002; Beuther et al. 2002) based on their infrared colors. These samples were then extended using data from the more sensitive Midcourse Space Experiment (MSX; Price et al. 2001) point source catalogue (Egan et al. 2003). One notable example is the Red MSX Source (RMS; Hoare et al. 2005) Survey, which used a combination of near- and mid-infrared colors to identify a large sample of MYSO candidates (Lumsden et al. 2002). Their initial sample was, however, contaminated by asymptotic giant branch (AGB) stars and evolved stars whose mass loss has stopped and dust shells became detached (post-AGB stars and planetary nebulae). These contaminating sources have been identified through a set of multi-wavelength observations (e.g. Urquhart et al. 2008) and were removed from the final sample (Lumsden et al. 2013). However, since the infrared emission traces heated dust, this sample is strongly biased towards the more evolved MYSO and H II region phases of high-mass star-formation.

The search for the earlier, thus colder stages began with the discovery of IR-dark clouds (IRDCs), which trace high dust column density (Perault et al. 1996; Egan et al. 1998; Carey et al. 1998). These clouds have been catalogued using MSX (Simon et al. 2006; Rathborne et al. 2006) and the more sensitive Spitzer Space Telescope (Peretto & Fuller 2003; Butler & Tarafdar 2009; Peretto & Fuller 2010; Rygl et al. 2010). Their physical properties have also been extensively studied since then (e.g. Pillai et al. 2006; Vasyunina et al. 2009; Ragan et al. 2012). Although IRDCs have been considered for a long time to be the initial stages for high-mass star-formation, some of them have been shown to be simply holes in the interstellar medium (Wilcock et al. 2012), and in fact only a small fraction of them is likely to sustain massive star-formation (Peretto et al. 2010; Kaufmann & Pillai 2010). As a consequence, IRDCs also represent a biased and incomplete sample of high-mass star-forming sites.

To unambiguously trace high column densities, the optically thin emission from dust in the millimeter/sub-millimeter regime is the best tool (André et al. 2000). Sensitive to both cold and warm dust, the majority of which, are sites of on-going star-formation. The search for the earlier, thus colder stages began with the discovery of IR-dark clouds (IRDCs), which trace high dust column density (Perault et al. 1996; Egan et al. 1998; Carey et al. 1998). These clouds have been catalogued using MSX (Simon et al. 2006; Rathborne et al. 2006) and the more sensitive Spitzer Space Telescope (Peretto & Fuller 2003; Butler & Tarafdar 2009; Peretto & Fuller 2010; Rygl et al. 2010). Their physical properties have also been extensively studied since then (e.g. Pillai et al. 2006; Vasyunina et al. 2009; Ragan et al. 2012). Although IRDCs have been considered for a long time to be the initial stages for high-mass star-formation, some of them have been shown to be simply holes in the interstellar medium (Wilcock et al. 2012), and in fact only a small fraction of them is likely to sustain massive star-formation (Peretto et al. 2010; Kaufmann & Pillai 2010). As a consequence, IRDCs also represent a biased and incomplete sample of high-mass star-forming sites.

Here we present results of one of these large-scale surveys, the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL).

1.2. ATLASGAL in the context of Galactic plane surveys

The ATLASGAL survey (Schuller et al. 2009) imaged the Galactic plane between Galactict longitude, $-60^\circ \leq l \leq +60^\circ$ and Galactic latitude $-1.5^\circ \leq b \leq +1.5^\circ$ at 870 µm with the LABOCA camera (Siringo et al. 2009) on the APEX Telescope (Güsten et al. 2006) in its first campaign. In a following step, an extension towards Galactic longitude $-80^\circ \leq l \leq -60^\circ$ and Galactic latitude $-2^\circ \leq b \leq +1.0^\circ$ was added. Altogether the total area of the survey covers $~ 420^2$ of the Galactic plane at a 19″ spatial resolution.

The ATLASGAL survey supersedes other ground-based surveys providing the most sensitive and complete view of the inner Galaxy at sub-millimeter wavelengths. So far only space based missions provide better sensitivity. In this context the ATLASGAL survey is outstanding because it provides a view of the thermal dust emission at a comparable angular-resolution at 870 µm as Herschel at 250 µm, and a 2× better spatial resolution than Herschel at 500 µm, where the dust emission is optically thin. It is therefore well suited to study deeply embedded objects, the majority of which, are sites of on-going star-formation.

ATLASGAL is well suited to complement other surveys of dust in the Galactic plane at various wavelengths, such as the mid-IR surveys with Spitzer (GLIMPSE at 3.6, 4.5, 5.6 and 8 µm; Benjamin et al. 2003) and MIPS at 24 µm (Carey et al. 2009) and WISE (3.6, 4.6, 11.8 and 22 µm; Wright et al. 2010) probing the warm dust. The Hi-Gal survey (Herschel Infrared Galactic Plane survey; Molinari et al. 2010b) uses the PACS and SPIRE instruments onboard Herschel to map the Galactic plane with unprecedented sensitivity from the far-IR to the sub-millimeter wavelength regime (at 70, 160, 250, 350 and 500 µm). It provides complementary information of the spectral energy distribution in the regime where the thermal emission of cold and warm dust peak (between 10-500 K). ATLASGAL also has a substantial overlap with the Bolocam Galactic Plane Survey (BGPS; Aguirre et al. 2011) at 1.1 mm and partially overlaps with the JCMT SCUBA-2 survey of the Galactic plane (Di Francesco 2008) at 850 µm. There are common complexes also covered by the HOBYSS program (Herschel imaging survey of OB young stellar objects; Motte et al. 2010). The Coordinated Radio and Infrared Survey for High-Mass Star Formation at 5 GHz, (CORNISH; Hoare et al. 2012; Purcell et al. 2013), and other surveys in the radio regime probe free-free emission of ionized gas surrounding OB type stars.

The combination of these surveys therefore provide a complete view of the spectral energy distribution (SED) from IR to radio wavelengths, which is necessary to probe the nature of dust clumps. This reveals purely dust sources, which can be starless or pre-stellar, mid-IR bright protostars which just started to heat up their surroundings and massive stars where the ionizing emission leads to the development of UC-H II regions which then expand becoming optically visible H II regions. The dust emission at 870 µm measured in the ATLASGAL survey is therefore sensitive to sources in all evolutionary stages with both cold and warm gas (Schuller et al. 2009; Urquhart et al. 2013a). The ATLASGAL survey has been used to study various objects in specific environments in the Galaxy and here we give

\footnote{Observing runs: 078.F-9040, 181.C-0885 (ESO); 079.C-9501, 081.C-9501 (MPIR); and Chilean data}
an overview of them. For a sample of Galactic bubbles, identified from Spitzer-GLIMPSE data, Deharveng et al. (2010) use ATLASGAL to study the dense and cold material at the borders of H ii regions. Beuther et al. (2013) use ATLASGAL data to reveal the Galactic structure. In a limited range of Galactic longitude (10° < ℓ < 20°), Taackenberg et al. (2012) use ATLASGAL to identify a population of starless clumps. In a series of papers the properties of dust clumps associated with various signposts of massive star-formation were determined. Urquhart et al. (2013b) studied the physical properties of sources from the Methanol-MultiBeam survey (Green et al. 2009), a sample of H ii regions from the CORNISH survey (Urquhart et al. 2013b) and MYSOs from the RMS survey (Urquhart et al. in prep). The projected image of dust lacks, however, any information on the line-of-sight distribution of the material, for which spectroscopic observations are required. Numerous molecular line follow-up observations have therefore been triggered by the ATLASGAL survey. The MALT90 project maps over 2000 ATLASGAL sources in 16 lines (Foster et al. 2011; Jackson et al. 2013). Wienen et al. (2012) presents an extensive follow-up campaign of the ~1000 brightest dust clumps in NH3 in order to determine kinematic distances and gas temperatures.

The first catalog of compact sources from the ATLASGAL survey is presented by Contras et al. (2013) and focuses on a limited range in Galactic longitude (−30° < ℓ < 21°). Here we aim to complement this work by covering the full area of the survey and at the same time specifically addressing the population of embedded, smaller size-scale objects (see Sect. 3.6) compared to Contras et al. (2013).

The paper is organized as follows: Sect. 2 describes the data processing. Sect. 3 presents the source extraction method and comparison with the previous catalog. Sect. 4 presents the catalog and the properties of the extracted sources. In Sect. 5 we compare the sources with mid-IR diagnostics to estimate their fraction associated with on-going star-formation and study their statistical properties. Then we present their global properties, such as the Galactic distribution and typical fluxes of quiescent and star-forming sources in Sect. 6. Based on these statistics we estimate a Galactic star-formation rate and formation timescales in Sect. 7. We summarize the results in Sect. 8.

2. Observation and data reduction

This paper is based on all data taken for the survey between 2007 and 2010. The observing strategy and the main steps of the data reduction procedure are described in detail by Schuller et al. (2009) and Contras et al. (2013). The data was reduced with the BoA software (Schuller 2012). Emission from larger scales was iteratively recovered until convergence was reached after 15 iterations.

The absolute position accuracy of the ATLASGAL survey has been discussed in detail in Contras et al. (2013). The astrometry of the dataset and the derived source positions are estimated to be accurate to the pointing accuracy of the telescope, which is ~ 2−3′′. The absolute flux uncertainty is estimated to be less than ~ 15% (Schuller et al. 2009). Variations in the sky emission (“sky-noise”) mimic emission from extended astronomical objects. Ground based bolometer arrays are therefore not well suited to measure extended emission, since the emission from larger angular scales is removed when subtracting the correlated noise from the maps. The final emission maps of the survey are sensitive to angular scales up to 2.5′′, thus the current data reduction is optimized to enhance compact sources. The final maps have been gridded on 3 by 3 degree tiles with ~ 4.5′ overlap between adjacent emission maps. The pixel size is 6′′ which is ~1/3 of the beam size. The data is publicly available at http://atlasgal.mpifr-bonn.mpg.de/

The average noise level is determined from the |b| ≤ 1° portions of the maps where the vast majority of the emission originates from and because the noise increases rapidly towards the edges of the maps due to a lower number of overlapping coverages. The noise was determined from a Gaussian fit to the distribution of the pixel values in the maps and is found to be on average ~70 mJy/beam over the whole survey region. The average noise varies (~20%) as a function of ℓ due to the non-homogeneous coverage of the observed regions and varying observing conditions (see Fig. 1). In the longitude ranges ℓ > 40° and ℓ < −40° the average noise increases to 70–90 mJy/beam, while in the central part of the plane the noise is ~ 50–60 mJy/beam. In the extension, between −80° ≤ ℓ ≤ −60°, the noise is higher (~ 110 mJy/beam) than in the main part of the survey due to fewer coverages and shorter observing time.

In the following we extract the population of compact sources in the Galactic plane using all ATLASGAL data. However, due to the increased noise in the extension, we base our analysis only on the main part of the survey within the ℓ ≤ ±60° in Galactic longitude range. The identified compact objects mainly correspond to starless, pre-cluster dense material, protostars, protoclusters, compact H ii regions, as well as over-densities in the clumpy and filamentary cloud structures.

Fig. 1. The rms noise level determined on the individual tiles of maps using a Gaussian fitting to the distribution of the pixel values between |b| ≤ 1°. The region analyzed in Contras et al. (2013) is indicated by dotted lines. The horizontal dashed line shows the average 0.07 Jy/beam noise level for the main part of the survey (|ℓ| ≤ 60°).

3. Source extraction

In the following we assume that the 870 µm emission arises from thermal continuum emission from dust and that the contamination from free-free emission is negligible. The filter of LABOCA admits a 60 GHz frequency range centered on 345 GHz (Siringo et al. 2009) thus covering the CO (3-2) rotational transition at 345.796 GHz and other lines. Here we do not account for any line contamination, nevertheless, as discussed
in Schuller et al. (2009), the contribution to the derived fluxes may be more than the usual 15% flux calibration uncertainty, but only towards the most extreme sources, such as hot molecular cores, strong outflow sources, and bright photon-dominated regions and is not likely to be an issue for the vast majority of the ATLASGAL sources.

### 3.1. Overview of source extraction algorithms

Systematic source identification algorithms have been developed to analyze ground-based millimeter/sub-millimeter maps, such as Clumpfind (Williams et al. 1994), and Gaussian source fitting in different implementations, originally developed by Stutzki & Güsten (1990). The arrival of fast mapping capabilities by the PACS and SPIRE instruments onboard Herschel boosted the development of various source-extraction algorithms. The space-based observations provide the possibility for efficient mapping, but also the imaging of a significant amount of large-scale emission, which can not be recovered by ground-based surveys. Therefore several new methods have been developed to deal with the extended emission and also to handle multi-wavelength data sets such as those of Herschel (e.g. MRE-GCL, Multi-resolution and Gaussclumps algorithm, Motte et al. 2010, CuTiX: Molinari et al. 2011, Getsources: Men’shchikov et al. 2012). A detailed overview on these different source-extraction algorithms, discussing their advantages and disadvantages is given in Men’shchikov et al. (2012).

The majority of these algorithms assume a uniform noise distribution which is not realistic, especially for ground based observations that may be done at different meteorological conditions, different elevations, etc. It is therefore unavoidable that large area ground-based surveys show varying noise levels over the survey region. The SExtractor algorithm (Bertin & Arnouts 1996) uses a ρ-clipping method to handle the varying noise level, and has been originally developed for optical and infrared images, identifying stars (point sources) and galaxies. However thermal emission from the spatially extended cloud structure usually shows a more complex morphology. For example, the population of compact sources is deeply embedded in dense clouds. Contreras et al. (2013) have successfully applied the SExtractor algorithm to a substantial part of the ATLASGAL survey (~30' < t < 21'). This method applied to dust emission maps pulls out properties of the whole clump as it is not optimized to separate compact emission from the more diffuse envelope. Therefore it can be considered to work similarly as a contouring algorithm like Clumpfind without any assumption on the source characteristics.

Another, in many ways complementary approach is to assume a certain characteristic or property for the embedded sources. The Gaussclumps algorithm (Stutzki & Güsten 1990, Kramer et al. 1998) was originally developed to identify coherent structures of 3-dimensional molecular line (position, position, velocity: p-p-v) data cubes, and assumes a Gaussian intensity distribution to identify structures. The interstellar medium exhibits a clumpy morphology with the embedded sources on much smaller spatial scales superimposed on this background emission. Since our main interest is to identify these more compact sources, i.e. cores and clumps, we base their identification on the assumption that they exhibit a Gaussian intensity distribution. The assumption of a Gaussian intensity profile is adequate for compact sources with sizes of a few times the beam (e.g. Motte et al. 2007, 2009), and which is referred to as the MRE-GCL method in the literature. It has been used to identify compact sources of thermal dust emission by different groups for complex regions, like W43 (Motte et al. 2003), Cygnus-X (Motte et al. 2007), and the NGC 6334-NGC 6357 complexes (Russiel et al. 2010). It has also been applied for smaller regions, such as RCW 106 (Mookerjea et al. 2004), NGC 2264 (Peretto et al. 2006) and G327.3-0.6 (Minier et al. 2009). The main steps are to first disentangle the compact sources from the more diffuse, extended emission of filamentary clouds. This is done by a multi-scale wavelet transformation that is used to filter out the larger scale structures (see examples in Fig. 2 Fig. A.1) and then use the Gaussclumps algorithm to extract sources. These steps of the method are described in more detail in the following two subsections, Sec. 3.2 and 3.3.

#### 3.2. Multi-scale decomposition

Molecular clouds exhibit structures at various scales and part of their material is organized into large-scale filaments (e.g. André et al. 2010; Molinari et al. 2010a; Kainulainen et al. 2011). Although ground based bolometers are insensitive to uniform diffuse emission, they recover a significant amount of extended structures of dust seen towards the Galactic plane. Since the ATLASGAL maps contain emission from 19''/2 up to 2.5 spatial scales, it is desirable to remove the extended emission in order to extract the properties of embedded sources.

At distances up to 1 kpc the spatial resolution of the survey corresponds to <0.1 pc physical scales, thus rather individual cores. Placed at larger, beyond 10 kpc distance this translates to >1 pc size-scale objects, therefore corresponding to cloud structures. As opposed to single complexes, the choice of a physical scale is not trivial since the whole Galaxy is seen in projection along the line-of-sight.

We therefore visually examined the structures at different scales aiming to identify the best spherically symmetric, centrally condensed compact objects. This way we choose to optimize the extraction method to be sensitive to structures with angular scales from the 19''/2 resolution element to ~50'', which translate to a physical scale of 0.4 – 1 pc at 4 kpc. This is also a reasonable physical scale for compact structures assuming that a large fraction of the sources lie at the typical distance of ~4 kpc (e.g. Wienen et al. 2012), while Peretto & Fuller (2010) finds that 95% of the IRDCs are at distances of <6 kpc with the mean distance between 3.5 kpc. Here we aim therefore to extract the properties of compact sources with typical size-scales of 0.4 pc to 1 pc, commonly noted as clumps (e.g. Bein & Tafalla 2007, Motte & Hennebelle 2009).

Since our primary interest is in these embedded sources, we systematically remove emission from cloud structures at larger scales that we consider as extended emission originating from the embedding cloud. To do this we decomposed the emission into different spatial scales using a wavelet transformation with the method of Starck & Murtagh (2006). Emission from smaller than twice the maximum required 50'' scale was then summed up. Due to the wavelet decomposition negative artifacts appear around bright sources and we have set these negative artifacts to zero in order to help the convergence of the algorithm (see Kramer et al. 1998 Motte et al. 2007). The emission with different scales is illustrated in Fig. 2 for an isolated source, see Fig. A.1.
3.3. Extraction of compact sources – Gaussclumps

Although Gaussclumps does not deal with varying noise levels, it is very important to consider the non-uniform noise distribution of the maps to avoid detection of spurious sources and missing genuine sources in a region with lower noise. To overcome this, we used the weight maps and calculated from pixel to pixel signal-to-noise maps using the formula: \( \text{snr} = \frac{\text{flux} \times \sqrt{\text{weight}}}{\text{rms}} \), where \( \text{flux} \) corresponds to the flux density in the emission maps and the weight is computed when combining signals of all bolometers into a map. The weight is related to the noise as \( \frac{1}{\text{rms}} \) where the \( \text{rms} \) is the standard deviation of the signals of the bolometers (see Schuller et al. 2009 for more details). The intensity of the weight maps exhibits variations of \( \sim 10\% \) on a 60′ scale, so the spatial variations are smaller than the expected size of compact sources. Therefore we use the signal-to-noise maps as the input files for the source extraction method, and use Gaussclumps with a threshold of \( \sim 5 \), which corresponds to \( 5 \times \) the local \( \text{rms} \). The choice of this threshold is justified in Sect. 3.4.

The position and size of the sources were derived from the output of Gaussclumps while the peak flux values were computed using the flux values from the \( \text{snr} \) maps multiplied by the noise level measured on the weight maps.

As a sanity check we have visually inspected all sources with outlying (i.e. the highest and lowest) fluxes and aspect ratios and found them to be genuine sources. We discuss the impact of the filtering on the extracted source parameters in App. A.1 and A.2.

All of the survey region was inspected for missed sources and we found that visible but undetected structures fall below the \( \text{snr} \) threshold used for the extraction.

3.4. Completeness limit

We estimate the completeness limit of our source extraction method by adding artificial sources into the input maps of Gaussclumps. Using the same input parameters as for the catalog we measure the number of extracted artificial sources as a function of peak flux, following a similar procedure described

Fig. 2. We show an example of the multi-scale decomposition towards the brightest region at 870 \( \mu \text{m} \) in the whole survey which hosts SgrB2(N) and SgrB2(M). The impact of flux loss due to filtering is the most severe towards this region. Contours start at 7.5 Jy/beam and increase on a logarithmic scale to 120 Jy/beam. Dotted circles mark the regions where the radial averaging has been done (see Sect. 3.3 and Fig. 5 for details). The beam size of 19.2′′ is shown in panel a). Panels a) to e) show maps with different scales of filtering: from no filtering to maps where background emission is increasingly removed. The catalog is generated from a filtering level corresponding to the e) panel, where emission until 2×50′′ scales is summed up. The peak flux density of the object in this case decreases by 20% from the original images to the most compact one, while the size decreases by only 10%. The f) panel shows the filtered \( \text{snr} \) map used as the input for the source extraction algorithm containing the same spatial scales as the e) panel. The scaling is logarithmic between 3 – 120\( \sigma \), contours start at 7\( \sigma \) increasing on a logarithmic scale.
by Contreras et al. (2013). For these tests we have used a simulated field of $20 \times 9^2$ size, which corresponds to 20 ATLASGAL tiles and injected 9989 artificial sources. This is similar to the total number of sources we find for the full survey. To mimic a uniform background noise the first set of artificial sources were injected on maps with a normal distribution of noise values with a standard deviation of $\sigma = 60$ mJy/beam. The injected sources have peak flux densities following a uniform distribution up to 1.5 Jy/beam, with $30''$ FWHM size, an aspect ratio of 1 and a Gaussian flux distribution in order to imitate spherically structured cores.

The second test was made with the same characteristics for the artificial sources, but injected on a background map with a varying noise level. For this we used a map with real observations, but smoothed with a Gaussian kernel of 31 by 31 pixel array which has a FWHM of 5 by 5 pixels in order to imitate the extended emission from molecular clouds. A third test was done using the maps with varying background noise and the same filtering level as for the full catalog. We run our extraction algorithm down to a fixed threshold of ~ 3$\sigma$ and therefore extracted sources down to 0.2 Jy/beam. This threshold was chosen to be lower than that used for the source extraction on the real data in order to explore the lower limits of our completeness.

As a consistency check we have compared the fluxes of the injected and recovered sources and find good agreement between these values for all three simulations. Fig. 3 shows the comparison between the injected and extracted peak flux densities for the case of normal noise distribution. In all of the simulations we find that the measured source properties lie close to unity compared to the injected parameters for high peak flux densities. Close to the detection threshold we see a deviation from unity with the measured fluxes being offset to slightly higher than the injected values. This offset is at most 1$\sigma$ (60 mJy) in the peak flux densities introducing <20% error in the peak fluxes for the weakest sources and is a result of flux boosting due to the constructive interference with the noise which determines the fitting of the peak flux.

Fig. 4 shows the detection ratio of the sources as a function of peak flux density, where we allowed a positional offset of 10$''$ between the artificial and the extracted sources. We find that our catalog is complete to 99.4% above 7$\sigma$, and 97% of the injected sources are recovered at 5$\sigma$. This was therefore chosen as a detection threshold for the extraction for the full survey. A lower value would result in a less reliable catalog and the completeness level at lower flux densities would also be limited, which is not desirable for statistical studies. We stress that below a 7$\sigma$ noise level, measured on the input maps, our catalog is not complete, and genuine sources may be missed. Our completeness level is comparable to that of other source extraction methods, such as the one used by Contreras et al. (2013).

3.5. Physical parameters of the compact sources

Since the sources are identified and extracted from maps where the extended emission was removed, the corresponding physical parameters, such as the size and the peak flux are different compared to the original emission maps. These parameters are more likely to reflect the real properties of the embedded compact sources as illustrated in Fig. 2 (another example is shown in Fig. A.1 for an isolated source) and in Fig. 5 where we show the azimuthally averaged intensity profile from the original and the filtered maps used for the source extraction. It illustrates that by removing the extended emission, the measurement of the Gaussian parameters of the embedded source improves. We have tested the impact of the multi-scale decomposition on the measured fluxes and sizes by extracting the sources using different scales. We found that the impact on the measured size is in most cases very small, because the majority of the sources are only marginally resolved, and their morphology is dominated by a compact emission. For the peak flux values we find that the difference is less than 20% for isolated sources, however in complex regions, especially for bright, massive clouds the extended emission contributes more to the total flux. This can be as high as 50% of the total flux in such regions (see also App. A for more details).
We measure the physical parameters of the sources using the formulae from Schuller et al. (2009) and assuming optically thin emission of dust at 870 μm. The column density is derived from:

\[
N(H_2) = \frac{F_\nu R}{B_\nu(T_d) \Omega \kappa \mu m_H} \tag{1}
\]

where \(F_\nu\) is the peak flux density, \(\Omega\) is the beam solid angle, \(\kappa\) is the mean molecular weight of the interstellar medium with respect to hydrogen molecules, which is equal to 2.8 (Kauffmann et al. 2008), and \(m_H\) is the mass of an hydrogen atom. We adopt here the same assumptions as Schuller et al. (2008), a gas-to-dust mass ratio (R) of 100, and \(\kappa = 1.85 \text{ cm}^2 \text{ g}^{-1}\), which is interpolated to 870 μm from Table 1, Col. 5 of Ossenkopf & Henning (1994). At our completeness level of 7σ, we are thus sensitive to column densities between \(7 \times 10^{11} - 4 \times 10^{22} \text{ cm}^{-2}\) for warm \((T_d = 30 \text{ K})\) and cold \((T_d = 10 \text{ K})\) gas, respectively. We estimate the mass as:

\[
M = \frac{S_\nu R d^2}{B_\nu(T_d) \kappa \nu} \tag{2}
\]

where \(S_\nu\) is the integrated flux and \(d\) corresponds to the distance of the sources. For a typical dust temperature of \(T_d = 15 \text{ K}\), our completeness limit corresponds to \(\sim 270 \text{ M}_\odot\) at 8 kpc and \(1 \text{ M}_\odot\) at 0.5 kpc. The ATLASGAL survey therefore probes all massive clumps in the inner Galaxy and in the < 1 kpc nearby regions intermediate-mass cores as well.

Since with ATLASGAL we probe the whole inner Galaxy, it is crucial to assess what fraction of the extracted sources may sustain high-mass star-formation. Motte et al. (2007) adopted a limit of 40 M\(_\odot\) for defining Massive Dense Cores (MDCs) based on an unbiased study of the high-mass star-forming complex, Cygnus-X. The sources were found to have an average size of 0.13 pc and the mass was calculated assuming a density profile of \(\rho(r) \propto r^{-2}\). Using high angular-resolution observations these MDCs have been confirmed to host individual high-mass protostars (Bontemps et al. 2010, Csengeri et al. 2011b). We extrapolate this definition to our average spatial resolution of 0.4 pc (see Sect. 5.3), and find that the same \(\rho(r) \propto r^{-2}\) density profile corresponds to minimum mass of \(\sim 125 \text{ M}_\odot\). However, as observed in Cygnus-X, it is very likely that MDCs are embedded in massive clumps on the 0.4 pc scale of our resolution. For example, the massive clump of DR21(OH) with 0.6 pc size is fragmented into 3 MDCs on a 0.13 pc scale. Each of these MDCs were shown to host individual high-mass protostars (Csengeri et al. 2011b). If the ATLASGAL clumps fragment on smaller than 0.4 pc scale, they should exhibit a shallower density profile. Therefore we estimate a minimum mass-range between the \(\rho(r) \propto r^{-2}\) density profile (extreme lower limit, \(\sim 125 \text{ M}_\odot\)) and a uniform density profile (extreme upper limit, \(\sim 1150 \text{ M}_\odot\)). We adopt here an average value of these two limiting cases of 650 M\(_\odot\) as an approximate threshold for ATLASGAL clumps likely to host MDCs and high-mass protostars. This is consistent with other studies similarly suggesting that clumps below 1000 M\(_\odot\) can as well potentially form massive stars as long as they are compact (e.g. Lada & Lada 2003, Urquhart et al. 2013).

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\(N(H_2)\) values by a factor of \(\sim 1.2\) to be consistent with other studies using \(\mu = 2.33\).

Our criterion for clumps to form massive stars is more selective compared to (Tackenberg et al. 2012), who adopt a mass limit of 1000 M\(_\odot\). They select on average larger structures with larger integrated fluxes. Our analysis yields on average 6 times lower masses due to the different source identification and a different \(\kappa\). Consequently, their mass limit corresponds to 1000 M\(_\odot\), 3 times more conservative.

The full catalog using SExtractor is available on this web-page: http://atlasgal.mpifr-bonn.mpg.de.
stars and galaxies, which show lower level of extended background emission than dust continuum from molecular clouds. Differences between the two catalogs come from the fact that the MRE-GCL method is more efficient identifying small and compact sources, while SExtractor is better suited to find larger size-scale sources. The two catalogs are therefore complementary in terms of source characteristics.

4. Compact sources in the Galactic plane

Here we present the result of the source extraction method described above. In total we have found 10565 sources in the $-60^\circ \leq \ell \leq +60^\circ$ longitude and $-1.5^\circ \leq b \leq +1.5^\circ$ latitude range, covering the I\textsuperscript{I} and IV\textsuperscript{th} Galactic quadrants. Table\textsuperscript{4} presents a sample of the compact source catalog, the full catalog is available in electronic form. The table structure is as follows: column (1) corresponds to the source id, then we give the source name (2), and the position in galactic coordinates (3, 4) and in J2000 equatorial coordinates (5, 6) (in hexadecimal format). The physical parameters of the sources follow: the beam convolved major ($\Theta_{\text{maj}}$) and minor axis ($\Theta_{\text{min}}$) in arc seconds (7, 8), the position angle of the fitted Gaussian measured from north to east (9), the average FWHM source size (beam convolved) (10) the peak flux (11) and the integrated flux (12) calculated assuming a 2D-gaussian shape for the sources: $S_* = F_* \times (\text{FWHM})^2$, where $F_*$ is the peak flux, FWHM is the geometric size of the source, $\text{FWHM}_{\text{maj}}$ is 19.2, the $\text{snr}$ determined from the weight maps (13).

As an example we show the identified sources in one of the most complex regions in the Galaxy in Fig\textsuperscript{5}. The left panel shows the large-scale emission of the W51 complex with a zoom on the most active site of star-formation associated with W51 Main (e.g., Gaume et al. 1993). The right panel shows the filtered image which was used for the source extraction. This illustrates how the algorithm performs in complex environments: the filtering clearly removes large scale emission, while all bright sources are recovered in the filtered maps.

We identified 296 sources in the extension between $280^\circ \leq \ell \leq 300^\circ$ longitude and $-2.0^\circ \leq b \leq 1.0^\circ$ latitude range towards the Carina-arm.

4.1. Flux Distribution

We show the distribution of the peak flux densities in Fig\textsuperscript{7} with a linear least-square fit to the flux bins above the completeness limit and determine a slope of $N/\Delta F_{\nu} \sim F_{\nu}^{\alpha}$, where $\alpha = -1.44 \pm 0.03$. As a comparison, we plot the sources of Contreras et al. (2013) in blue, which shows an identical slope of $\alpha_{\text{Cont}} = -1.47 \pm 0.04$. Despite the differences of the extraction methods, the two distributions compare well and we find the derived slopes to be consistent.

The distribution of the integrated intensity is shown in Fig\textsuperscript{8}. Here we find larger differences between the results obtained by Contreras et al. (2013) and our method. We derive systematically lower integrated intensities for the individual sources compared to Contreras et al. (2013), and also we find fewer sources with large integrated flux. This illustrates the differences in the concept of the two catalogs, also discussed in Sect. 3.5. Our method is better at identifying centrally condensed, more compact objects while Contreras et al. (2013) extracts more irregular

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\textsuperscript{7} CDS reference, http://atlasgal.mpifr-bonn.mpg.de

\textsuperscript{8} We determine the geometric average source size from the geometric mean of the Gaussian axes: $\text{FWHM} = \sqrt{\Theta_{\text{maj}} \times \Theta_{\text{min}}}$

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![Fig. 7. Distribution of the peak flux density of the detected sources. The ATLASGAL sources from the current paper are shown in black histogram with grey color. Blue line shows the sources from Contreras et al. (2013). Black dashed line shows the measured slope of the distribution, and green line indicates the star-forming ATLASGAL clumps (see Sect. 5 for details). A black dotted line corresponds to our $7\sigma$ completeness limit when using an average of 70 mJy/beam noise level. Fit to the slope of the distributions are shown in dashed colored lines. We note that here we show the source count per bin, while in Rosolowsky et al. (2010) and Contreras et al. (2013) the differential source count, $\Delta N/\Delta F_{\nu}$, is shown.](image-url)
Fig. 6. Left: Slice of the ATLASGAL survey showing the active star-forming region, W51, which contains both diffuse emission and compact sources. Color scale starts at a 0.1 Jy/beam and goes to 40 Jy/beam. Dark gray contours start from 3σ level (0.21 Jy/beam) and continue show 10σ, 20σ, 40σ, 80σ, 160σ, 320σ and 500σ. Green circles show the position of the extracted sources. A zoom towards the brightest continuum sources is shown in the inset, also known as W51 Main. Right: The same region as on the left panel but with from emission larger than 100″ scale removed.
Table 1. Dust condensations identified in the ATLASGAL survey.

| Id     | Name           | Ra [J2000] | Dec [J2000] | θmaj [arcsec] | θmin [arcsec] | PA [°] | FWHM [arcsec] | $F_r$ [Jy/beam] | $S_r$ [Jy] | snr   |
|--------|----------------|------------|-------------|---------------|---------------|-------|---------------|----------------|-----------|-------|
| 1      | G300.1627−0.0899 | 12:27:08.6 | −62:49:51.6 | 33            | 23            | 97    | 28            | 1.18           | 2.51      | 12.44 |
| 2      | G300.2169−0.1106 | 12:27:35.9 | −62:51:24.2 | 31            | 26            | 21    | 29            | 1.04           | 2.40      | 11.14 |
| 3      | G300.5038−0.1763 | 12:30:03.5 | −62:56:50.4 | 25            | 24            | 88    | 24            | 3.31           | 5.56      | 32.88 |
| 4      | G300.8250+1.1517 | 12:33:40.9 | −61:38:51.0 | 32            | 25            | 42    | 28            | 1.52           | 3.43      | 12.26 |
| 5      | G300.9097+0.8811 | 12:34:14.5 | −61:55:23.4 | 39            | 29            | 28    | 34            | 1.36           | 4.32      | 11.63 |
| 6      | G300.9688+1.1456 | 12:34:53.2 | −61:39:47.3 | 32            | 28            | 125   | 30            | 6.54           | 16.16     | 53.74 |
| 7      | G301.0140+1.1137 | 12:35:15.0 | −61:41:52.2 | 32            | 25            | 59    | 29            | 1.09           | 2.51      | 10.47 |
| 8      | G301.1164+0.9596 | 12:36:02.1 | −61:51:28.6 | 51            | 34            | −21   | 41            | 1.61           | 7.71      | 13.46 |
| 9      | G301.1169+0.9771 | 12:36:02.8 | −61:50:25.9 | 40            | 33            | 80    | 36            | 1.61           | 5.89      | 14.69 |
| 10     | G301.1365−0.2256 | 12:35:35.2 | −63:02:31.9 | 26            | 22            | 102   | 24            | 21.43          | 34.55     | 120.43|
| 11     | G301.1385+1.0092 | 12:36:14.7 | −61:48:35.0 | 48            | 33            | 127   | 40            | 1.06           | 4.68      | 10.01 |
| 12     | G301.6798+0.2456 | 12:40:33.1 | −62:35:59.1 | 28            | 24            | 81    | 26            | 1.41           | 2.59      | 11.77 |
| 13     | G301.7313+1.1038 | 12:41:17.6 | −61:44:39.6 | 39            | 31            | 157   | 35            | 2.07           | 6.89      | 18.53 |
| 14     | G301.7414+1.1013 | 12:41:22.6 | −61:44:50.4 | 38            | 28            | 128   | 33            | 1.29           | 3.90      | 12.53 |
| 15     | G301.8138+0.7811 | 12:41:53.3 | −62:04:12.1 | 27            | 26            | 44    | 26            | 1.46           | 2.80      | 11.38 |
| 16     | G302.0208+0.2517 | 12:43:31.0 | −62:36:22.0 | 35            | 25            | 15    | 30            | 2.06           | 5.14      | 17.54 |
| 17     | G302.0318−0.0607 | 12:43:31.7 | −62:55:07.4 | 30            | 27            | 18    | 28            | 2.62           | 5.95      | 24.47 |
| 18     | G302.0327+0.6254 | 12:43:43.0 | −62:13:58.6 | 27            | 21            | 65    | 24            | 1.49           | 2.39      | 14.40 |
| 19     | G302.3912+0.2804 | 12:46:44.4 | −62:35:11.3 | 37            | 27            | −28   | 32            | 2.12           | 6.08      | 22.71 |
| 20     | G302.4861−0.0310 | 12:47:31.4 | −62:53:58.0 | 30            | 25            | 74    | 27            | 1.89           | 3.96      | 17.65 |

Notes. The full table is available only in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.125.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A&A/.

Fig. 8. Distribution of the integrated flux density of the detected sources. Black dashed line shows the measured slope of the distribution, green line shows the same distribution for the star-forming ATLASGAL clumps (see Sect. 5 for details). The blue histogram shows the sources from Contreras et al. (2013), the cloud structure mimicking embedded sources or simply the blend of several sources.

5. Mid-IR diagnostics to characterize star-formation activity

Mid-IR emission traces warm dust, generally heated by embedded protostars, (M)YSOs, OB stars or evolved stars undergoing mass-loss. Dust surrounding evolved stars is less frequently detected than from protostars. Only a handful of such objects up to a distance of 5 kpc are detected at 870 μm with LABOCA within the sensitivity limit (on average σ ~ 70 mJy/beam) of ATLASGAL (Ladjal et al. 2010). Since the majority of the evolved stars are expected to emit weakly in the sub-millimeter the ATLASGAL sources are expected to be dominated by young, star-forming objects. As a consequence, their association with mid-IR sources can generally be used as a proxy to trace ongoing star-formation.

MSX surveyed the Galactic plane at mid-IR wavelengths with an angular resolution (18′′ at 8–21 μm) similar to that of the ATLASGAL survey. With a higher spatial resolution and sensitivity, surveys with the Spitzer and WISE space telescopes uncover a larger population of mid-IR sources in the Galactic plane. The multi-color Spitzer GLIMPSE and MIPS surveys probe fainter than young or lower mass protostars and they represent to date the highest spatial resolution and brightness sensitivity at mid-IR wavelengths. However, due to source confusion it is not straightforward to unambiguously associate Spitzer sources with dust peaks and the line of sight contamination from chance alignments with field stars is high. MIPS at 24 μm has only a factor of 2 higher sensitivity and an angular resolution of 6′′ (Carey et al. 2009) compared to WISE at 22 μm with 12′′ resolution. Since here we only study the statistical properties of the mid-IR associations with ATLASGAL sources, the best combination of surveys are the MSX and WISE datasets with available point source catalogs. They cover a continuous brightness sensitivity from the brightest sources in the Galactic plane to weaker, deeply embedded young protostars and have a comparable angular resolution as ATLASGAL at 870 μm.

Contreras et al. (2013) used data only from MSX at 21.3 μm to give a crude estimate on the proportion of star-forming clumps of ATLASGAL. We base the characterization of the mid-IR content of dust clumps using the 21.3 μm filters on MSX (E-band), and the 22 μm filter on WISE (band 4). The former provides a sensitivity down to ~ 2 – 6 Jy (Egan et al. 1999), while the latter has a 5σ point source sensitivity in unconfused regions of 6 mJy (Wright et al. 2010). MSX suffers from saturation only for the brightest, few hundred Jy bright sources, and although the WISE 22 μm band starts to saturate at ~10 Jy reliable photometry can be extracted up to 330 Jy by fitting the wings of the PSF (Cutri et al. 2012). Therefore the two catalogs have a substantial overlap in sensitivity (see also Sect. 5.5) and combining these...
We have searched for MSX counterparts of ATLASGAL sources in this angular separation and with detectable flux at 21.3 µm. This corresponds to 16% of the total ATLASGAL sources (Table 2) and is a more conservative estimate than the 34.8% found by Contreras et al. (2013). Using a similar 30′ search radius as Contreras et al. (2013), we find the same fraction of the sources with an MSX counterpart.

We compare the color properties of these 16% matches with the color selection criteria used in the literature to search for embedded massive objects. We find that 97% of the sources fulfill the minimum criteria of $F_A > F_D$, which are the flux measurements at 14.65 µm (D-band) and 21.3 µm (E-band) and corresponds to a rising SED towards longer wavelengths. Schuller et al. (2006) use a selection criteria of $F_E / F_D \geq 2$, and from our matches we find that 1165 fulfill this, which is 77% of the sources with reliable flux measurements in both of these bands. Lumsden et al. (2002) adopts a less conservative requirement by using $F_E \geq 2 \times F_A$ and we find that 86% of our matches fulfill this, where $F_A$ corresponds to the flux in the A-band of MSX (8 µm). We note that extending the match radius to 30″ leads to a lower fraction of sources fulfilling these color properties, suggesting that the larger match radius would contain more sources with chance line-of-sight alignment or merging of nearby sources with different evolutionary status. Our position restricted estimate of the mid-IR content of ATLASGAL sources therefore corresponds to mostly embedded objects, while it is likely that the Contreras et al. (2013) matches include more significant contamination of chance alignment sources.

Since MSX has the highest sensitivity in the 8 µm band (0.1-0.2 Jy, Egan et al. 2002), we derive source counts of ATLASGAL matches in this band as well following the same method as described above. Similarly as above, here we derive a 13″ distance-limit and find 2238 sources matched to dust condensations. This number represents 21% of the ATLASGAL sources. Out of these, 1647 fulfill our selection criteria of the 21 µm matches, the rest are new associations. From these sources (only detected at 8 µm and not at 21 µm) we find 130 sources which are only detected at the shortest wavelengths (i.e. not detected in the C and D bands), suggesting that some of these new associations may be contaminated with evolved stars or PDR emission features. Therefore, despite of the higher sensitivity, we do not significantly increase the fraction of star-forming clumps using the 8 µm of MSX instead of the 21 µm band.

We note that between 8 µm and 22 µm not only the heated dust from the inner envelope emits, but there is diffuse emission from polycyclic aromatic hydrocarbon (PAHs) in the surrounding nebulosity. For the most complex region in the Galactic center Schuller et al. (2006) estimates 10% of the sources to be actually diffuse PDR emission rather than protostellar sources.

### 5.1. Association with MSX

We have searched for MSX counterparts of ATLASGAL sources within a 60″ search radius using the MSX Point Source Catalog (PSC) v2.3 (Egan et al. 2003). In the next step we determined a more appropriate matching radius by fitting a Gaussian to the normalized distribution of the angular separation between the MSX sources and ATLASGAL peak positions and then take 3σ as a match radius corresponding to ~13″ (Fig. [10]).

We find a total number of 1669 sources to have a corresponding MSX source within this angular separation and with detectable flux at 21.3 µm. This corresponds to 16% of the total ATLASGAL sources (Table 2) and is a more conservative estimate than the 34.8% found by Contreras et al. (2013). Using a similar 30″ search radius as Contreras et al. (2013), we find the same fraction of the sources with an MSX counterpart.

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#### 5.2. Association with WISE

Since WISE is more sensitive than MSX in all bands (by a factor of 500 at 21 µm), there is a higher probability of chance alignment between WISE and ATLASGAL sources. These can be field stars, low-mass YSOs and brown dwarfs from the foreground, and evolved stars. In the following we use the WISE point source catalog (Wright et al. 2010), and with a 30″ search radius we find a 96% match between ATLASGAL and WISE sources. We investigated the color properties of these first associations based only on positional coincidence in order to get a...
first hint on their nature. In fact, as expected, we found that such associations are largely contaminated by chance alignment with field stars.

It is necessary therefore to determine a more reliable estimate of the number of embedded mid-IR sources associated with ATLASGAL clumps by eliminating chance alignments as far as possible. For this we first limited the search radius to find the best potential matches (Fig. 10) using a similar strategy as was discussed above for MSX (see Sect. 5.1). However, given the large number of WISE matches, we study the distribution of the angular offset between mid-IR and dust peaks only using embedded sources with characteristic red colors ($F_{\mathrm{3.6\mu m}}/F_{\mathrm{8.0\mu m}} > 0.75$ and $F_{\mathrm{4.5\mu m}}/F_{\mathrm{12\mu m}} < 4$ S. Lumsdenc priv. comm.) We arrive to a similar search radius of 10′′, as for MSX. For the eventual matching between the ATLASGAL and WISE positions we do not use any color requirements, but the above derived limiting angular offset. We then put a further constrain on the matched sources by requiring a S/N > 10 for the 22 µm band WISE measurements in order to ensure their nature of embedded sources instead of a chance alignment with a field star or evolved stars, which are not detected at 22 µm (see e.g. Schuller et al. 2006). We discuss in more detail the justification and the color properties of these matches in Sect. 5.4

With these selection criteria we find 3151 ATLASGAL sources to have a WISE association. This corresponds to 30% of all the ATLASGAL sources.

From these matches we find that only a negligible fraction have S/N lower than 2 or a bad quality flag at 12 µm (band 3). Therefore the majority (89%) of our matches are detected at least in two WISE bands. Interestingly, we find that 97% of these matches have a measured flux at 4.5 µm (band 2) with a S/N greater than 2 (this value drops to 93% when restricting to S/N > 10). In the 4.5 µm and the 12 µm bands we find that 86% of the sources are detected with S/N > 2. At the shortest wavelengths (3.6 µm, band 1) 89% of the matched sources have fluxes above 2 S/N. Altogether 82% of our matches (2559 sources) have fluxes measured in all four bands above S/N > 2.

From these 2559 sources, 2481 (97%) fulfill the [3.6] > [4.5] > [12] > [24] criteria corresponding to rising SEDs in the mid-IR wavelength range. We find that 96% of them also fulfill the red object selection criteria used above ($F_{\mathrm{3.6\mu m}}/F_{\mathrm{8.0\mu m}} > 0.75$ and $F_{\mathrm{4.5\mu m}}/F_{\mathrm{12\mu m}} < 1$), while 99% of them fulfill the $F_{\mathrm{3.6\mu m}} > 2xF_{\mathrm{12\mu m}}$ criteria, which is similar to that of Lumsdenc et al. (2002). The majority of these associations are therefore reddened, most likely embedded star-forming objects. We study in more detail the color properties of this sample in Sect. 5.4

In the following we refer to ATLASGAL sources with associated mid-IR emission as star-forming clumps, while to the rest of the sources as quiescent. They represent a lower limit to the true proportion of star-forming sources since there is likely to be a number of clumps associated with embedded sources that fall below the 10σ detection threshold we used for the WISE catalog.

5.3. Correlation between 21 µm and 870 µm fluxes of star-forming ATLASGAL sources

Comparing the 21 − 22 µm flux densities between the MSX and WISE sources, we find that 1308 sources are found in both catalogs. To check our independently matched ATLASGAL sources with MSX and WISE, we show in Fig. 11 the comparison of the 21 µm flux density from the two catalogs. These independently derived flux densities from both surveys show a good correlation (with a Pearson correlation coefficient of 0.88 for sources between 10 − 80 Jy fluxes), however it is also clear that below ~10 Jy the flux measurements of MSX show an increased scatter. This is fully consistent with the varying noise level in the MSX data at different positions in the Galactic plane leading to less reliable measurements at the lower flux limit. For the brightest sources the WISE photometry seems to give systematically higher fluxes.

Taking into account this overlap between the two catalogs we arrive at a total number of 3483 associations at 21-22 µm with ATLASGAL sources. This is 33% of the total number of dust condensations from the ATLASGAL catalog. This result compares well with Contreras et al. (2013), who derived an upper limit on the fraction of star-forming clumps of ~50% using a less robust test for mid-IR emission with MSX. Here our matching criteria is more conservative to associate embedded sources with the ATLASGAL clumps (see also Sect. 5.4) resulting in a more robust sample. Therefore our derived fraction is a strict lower limit of the fraction of star-forming dust clumps in the inner Galaxy.

Fig. 12 shows the measured 22 µm flux densities from WISE and MSX versus the 870 µm flux density from ATLASGAL. The mid-IR flux density seems to increase with increasing submillimeter flux density, in particular the brightest dust clumps exhibit brighter 22 µm fluxes. We determine the Pearson coefficient to check for correlation between these two parameters using the WISE sources with fluxes between 10 − 300 Jy, where the photometry is the most reliable. We obtain a correlation coefficient of 0.29 with a significance value of < 0.001 which suggests a weak correlation between these parameters. As a comparison we plot a relation of $S_{22\mu m} \sim S_{870\mu m}$ to highlight the trend seen in the data. This may reflect that the more massive and luminous YSOs form within more massive dust clumps producing the distinct tail of the distribution, however distance and temperature effects may also play a role.

We also show in Fig. 12 the 22 µm flux density limit corresponding to a ZAMS B3 type star with a bolometric luminosity of $10^4 L_\odot$ at 1.4, and 8 kpc distance based on the color properties defined by Wood & Churchwell (1989) and adopted here following Motte et al. (2007). We also show the mass-limit required to host MDCs, precursors to high-mass stars, corresponding to 650 $M_\odot$ (see Sect. 5.4) at these distances. We adopt here a dust temperature of 18 K, because at larger scales the dust temperature is dominated by the interstellar radiation field at approximately this value (Bernard et al. 2010). Similar values have been used by Motte et al. (2007), who adopt T = 20 K for MDCs and Wienen et al. (2012), as well, who determine a gas kinetic temperature of 17 K for a sample of ATLASGAL clumps.

For 1, 4 and 8 kpc this mass-limit translates to a submillimeter flux density limit of 102.6, 6.4, 1.6 Jy, respectively in order to potentially form high-mass stars. To eventually determine the fraction of massive clumps distance information is essential (Wienen et al. 2012).

Fig. 13 shows the histogram of the ratio of the 22 µm and 870 µm fluxes. We find a broad range for this flux ratio with a peak around 1. We plot also the ATLASGAL-MMB, the ATLASGAL-CORNISH and the ATLASGAL-RMS associ-
The MMB sources tend to show a smaller flux ratio, than the CORNISH and RMS samples. We note, however, that the CORNISH sample can be considered as a subsample of the RMS sources as they consist of MYSOs and HII regions. The peak of the distribution for all star-forming ATLASGAL sources is shifted towards smaller flux ratios than for the MMB and more evolved samples suggesting an evolutionary trend with lower flux ratios corresponding to colder sources.

**Fig. 10.** Distribution of the normalized distance between the dust continuum peaks and the mid-IR sources within 30″. Black line shows all sources from the WISE catalog, while the red line corresponds to the distribution of only the red sources (see text for details). As a comparison the same distribution for all MSX sources is shown in gray. Dashed lines show the Gaussian fits to these distributions, the maximum angular distance between mid-IR sources and ATLASGAL sources was determined as 3σ from this and is shown in dashed line.

**Fig. 11.** Comparison of the WISE 22 μm and MSX 21 μm fluxes for the sources that are found in both catalogs. Red dashed line shows a robust linear fit with a slope of 0.71 ± 0.01.

5.4. Infrared colors of ATLASGAL sources

We use the WISE matched ATLASGAL sources which have measured fluxes above 2 S/N in all bands (2559 objects, ~25 % of the identified ATLASGAL sources) to study their characteristic colors. To demonstrate the results of these matches
we show a 3-color composite image in Fig. 14 with the star-forming ATLASGAL sources indicated together with all the WISE sources found within a 30′ search radius. We also use the list of ATLASGAL matched MMB associations (Urquhart et al. 2013b). CORNISH sources (Urquhart et al. 2013b) and RMS sources (Urquhart et al., in prep.) to illustrate the location of these sources with a known evolutionary stage on these plots. In general there are several WISE sources found within the 30′ search radius, and a substantial fraction of them are field stars appearing in blue on the figure. The requirement of emission at 22 µm, however, eliminates a major fraction of these sources.

As shown in Fig. 15 (as well as Figs. B.1-B.4) the majority of these matches separate well from field stars in the color-color space, suggesting that the contamination of chance alignments is small. Clearly, the mid-IR sources associated with ATLASGAL clumps are deeply embedded showing characteristic reddened colors. Their average colors are summarized in Table 3. The outlying points on the diagram likely correspond to mismatched sources, where our method erroneously associated a nearby field star to the ATLASGAL source. This may happen in complex regions affected by saturation, where the 22 µm flux measurement in the WISE catalog is flagged, but there is a nearby red source which can be a chance alignment.

Comparing the positions of embedded H II regions, RMS and MMB sources in Fig. 15 we see that especially the former two occupy a well defined region with colors between 1.5 < [3.4]-[4.6] < 6 and 2 < [12]-[22] < 8. These sources correspond to more evolved stages of high-mass star-formation, H II regions and MYSOs. The H II regions seem to occupy a well-determined region of the plot, while the RMS sources show more dispersion, likely because this sample is a combination of MYSO and H II regions. The largest scatter is seen for the MMB sources, which includes many of the more extreme reddened objects than the two other samples. This is consistent with the general view on the occurrence of Class II methanol masers, which predominantly trace high-mass star-formation, and are also frequently found around UC-H II regions (e.g. Urquhart et al. 2013a).

A large fraction of the unclassified ATLASGAL sources are spread in the color-space, similarly to the MMB sources suggesting that they may host the early stage of intermediate- and high-mass star-formation. There are several sources with moderately reddened colors and they are likely low- to intermediate-mass nearby star-forming cores. Using this plot we identify a number of highly reddened extreme sources which have not been revealed by the other surveys. These may be of potential interest to study in greater detail.

6. Galactic distribution of star-forming and quiescent ATLASGAL sources

6.1. Galactic longitude

The distribution of quiescent and star-forming ATLASGAL sources as a function of Galactic longitude is shown in Fig. 16. With over 10 000 sources we are able to trace various aspects of the Galactic structure. The strongest peak corresponds to the Galactic center region, with the highest number density of ATLASGAL sources. We see additional over-densities toward the direction of the Scutum-arm, the Norma-arm and Sagittarius-arm. In addition there are several known star-forming complexes appearing as statistically significant (> 7σ) peaks. The G305 complex stands out from the average source density, but we find other peaks indicating massive dust complexes, such as those around $\ell = 327^\circ$, $\ell = 333^\circ$ towards the Norma-tangent and $\ell = 337^\circ$, which is in the direction of the 3-kpc arm. These are spatially very extended complexes rich in embedded sources.
The $\ell = 333^\circ$ complex contains sources mostly at about 3.5 kpc (Simpson et al. 2012) in the Crux arm, between the Sagittarius- and Norma-arms along the line of sight (Bronfman et al. 2000). The source counts in Fig. 16 are likely to be lower beyond $\ell = 327^\circ$, because there is only one arm on the line of sight with the Sagittarius-arm being quite out of the plane. Likewise, the $\ell = 337^\circ$ region is in the tangent region of the $\ell$-kpc arm, but there is strong molecular emission both from the Norma and the Crux spiral arms. Therefore the peaks in Fig. 16 are related to the superposition of spiral arms on the line of sight. We also find a narrow peak toward $\ell = 345^\circ$. In this region there are several clouds spread over relatively large Galactic latitudes between $b = -0.9^\circ$ to $b = 1.3^\circ$. These features are all found within a very narrow Galactic longitude range of $345.2^\circ < \ell < 345.5^\circ$, and as a consequence appear as a very narrow peak on Fig. 16. This complex has been studied in more detail in López et al. (2011).

The relatively nearby complexes of NGC 6334 and NGC 6357 (Russel et al. 2010) also appear. The peaks at positive Galactic longitudes at $\ell = 10 - 12^\circ$ correspond to the complexes associated with W31 and W33, and there is a clear excess of sources around $\ell = 15 - 17^\circ$ dominated by the known star-forming regions M16 and M17. There are other peaks associated with mini star-burst regions like W43 and W51. Interestingly, the active star-forming region, W49, does not appear as a prominent peak. This can be explained due to its larger distance of sources from the line of sight compared to the W49 region, which is therefore much lower than based only on mid-IR diagnostics. This can be partly explained with contamination of the previous samples with evolved stars, which has been claimed for the Wood & Churchwell (1989) sample by Becker et al. (1994), who estimate the Galactic scale height for dust condensations in the Galactic plane. As a comparison, the normalized distribution the star-forming ATLASGAL sources is asymmetric and shows a characteristic shift towards negative latitudes (Fig. 17). We determine an offset of $0.076^\circ \pm 0.006^\circ$ to the peak of the distribution, which is very similar to the value of $0.07^\circ$ determined by Beuther et al. (2012). Other studies using similar datasets have also reported this shift (e.g. Schuller et al. 2009, Rosolowsky et al. 2010), likely due to using various other tracers of (massive) star-formation, i.e. UC-H$\alpha$ regions, (Bronfman et al. 2000), GLIMPSE YSOs (Robitaille et al. 2008), and molecular gas (Cohen & Thaddeus 1977, Bronfman et al. 1988). This shift is larger when using only IVth quadrant sources. However, this is not seen for samples of ATLASGAL sources associated with UC-H$\alpha$ regions and MMB sources. It is therefore likely that in ATLASGAL a large number of local clumps are seen tracing the Sun’s position off the Galactic plane.

We estimate the Galactic scale height for dust condensations using an exponential function and find that a value of 0.32$^\circ$ gives a good fit to the data. This means that the majority of dust sources are confined to a very narrow region around the Galactic midplane. As a comparison, the scale height of OB stars from IRAS is 0.6$^\circ$ derived by Wood & Churchwell (1989), which is similar to the 0.8$^\circ$ using MSX data to select OB type stars by Lumsden et al. (2002). Our estimate for the embedded stages is therefore much lower than based only on mid-IR diagnostics. This can be partly explained with contamination of the previous samples with evolved stars, which has been claimed for the Wood & Churchwell (1989) sample by Becker et al. (1994), who estimate the 0.4$^\circ$ scale height using UC-H$\alpha$ regions. Recent studies suggest a lower scale height closer to the value suggested from ATLASGAL (Walsh et al. 2011) estimates 0.4$^\circ$ using H$\alpha$ masers, similarly to Urquhart et al. (2011). Our estimate of a 0.32$^\circ$ scale-height corresponds to 47 pc at 8.4 kpc (Reid et al. 2009), which is the same as derived by Beuther et al. (2012).

We also report here inhomogeneities in the distribution of IVth and I$^\text{rd}$ quadrant sources. The most prominent is an excess in sources at negative latitudes around $\sim -1.0^\circ$. This bump seems to be associated to sources from the IVth quadrant. As a comparison, the normalized distribution the star-forming ATLASGAL sources is shown in green in Fig. 17. The star-forming ATLASGAL sources are well fitted with the same scale height as for the total distribution.

7. Quiescent and star-forming dust clumps: clues to star-formation processes and time-scales

The ATLASGAL survey provides an unbiased view of the embedded stages of massive star-formation from the onset of collapse to the emergence of H$\alpha$ regions. Therefore it provides
7.1. Properties of quiescent and star-forming clumps

In Fig. 7 we show the flux density distribution of ATLASGAL sources with mid-IR counterpart, i.e., embedded sources with ongoing star-formation, corresponding to 33% of the ATLASGAL sources (i.e., both MSX and WISE associations). Their peak flux distribution is found to be very similar to that of all ATLASGAL sources and we derive a slope of \( \alpha \approx -1.25 \pm 0.04 \). This value suggests a shallower distribution of the peak fluxes compared to that of all ATLASGAL sources, although this is clearly due to the lower number of star-forming ATLASGAL sources at the lower peak flux-density range. We note that the distribution of the peak flux density exhibits this uniform scaling over more than two orders of magnitude for both star-forming and all ATLASGAL clumps.

To further investigate the origin of this shallower distribution, in Fig. 18 we show the beam averaged flux density versus the fraction of star-forming ATLASGAL sources compared to all sources. Clearly, the fraction of star-forming clumps increases with increasing peak flux density suggesting that the vast majority of the brightest clumps are actively forming stars. This fraction seems to be a constant of \( \sim 0.75 \) within the errors for all sources above a beam averaged flux density of 5 Jy, corresponding to \( 0.7 - 4.2 \times 10^{23} \) cm\(^{-2}\) column density for warm (\( T_d = 30 \) K) and cold (\( T_d = 10 \) K) gas. Adopting an average distance of 4.5 kpc and a temperature of 18 K, this threshold gives a similar value to the 650 M\(_{\odot}\) that we obtained from the extrapolation of the MDCs in Cygnus-X from Motte et al. (2007) to the ATLASGAL survey (see Sect. 3.5) suggesting that these sources could potentially sustain high-mass star-formation. This increase in the fraction of star-forming sources may also indicate that there is a change in the star-formation process in massive clumps, although this transition is likely smeared to a continuous trend due to distance effects in Fig. 18.

We point out that there is only a minor fraction of massive ATLASGAL clumps above this threshold that do not seem to harbor mid-IR embedded sources. These massive, quiescent looking sources are interesting because they may be ei-
for a B3 type star with $10^3 I_\odot$ (see also Sect. 5.3) which corresponds to ~75 mJy at the far side of the Galaxy at 20 kpc. This is above the WISE sensitivity limit, therefore we are sensitive to all B3 and earlier type massive stars in the Galaxy.

Based on the assumption that with WISE and MSX we cover all high-mass star-forming sites within 20 kpc, we derive a crude estimate here for the current rate of star-formation for these deeply embedded objects.

The time-scale for the protostellar evolutionary stage for high-mass stars is debated. If the accretion rate is constant and is at the order of the observed $~10^{-7} M_\odot$ yr$^{-1}$ (Klaassen & Wilson 2007), at least $10^5$ years or longer are needed to build up a 10 $M_\odot$ star. On the other hand, there are a few studies suggesting that the time-scale for high-mass protostars can be shorter (e.g. Motte et al. 2007, or similarly long Duarte-Cabral et al. 2013) as for low-mass proto-stars, where a life-time at the order of $~10^5$ yr has been derived (Evans et al. 2009).

Theoretical models predict a star-formation time-scale at the order of $10^5$ yr (e.g. McKee & Tan 2003; Offner & McKee 2011). We adopt therefore the so far best observationally derived value of $3 \pm 1 \times 10^5$ yr by Duarte-Cabral et al. (2013) for the highly embedded stage and account for a multiplicity of $\sim 2$, which has been seen towards MDCs in Cygnus-X at high angular-resolution (Bontemps et al. 2010). We estimate a $dN/dt = \frac{2.4 \pm 0.81}{3.1 \times 10^5}$ yr$^{-1}$ for the current formation rate for high-mass stars. Assuming that they form on average $8 \sim 10 M_\odot$ stars we estimate a star-formation rate of $0.21 \pm 0.07 M_\odot$ yr$^{-1}$ for massive stars.

Taking the IMF of Kroupa et al. (1993) and neglecting the brown-dwarf population (objects with $M < 0.08 M_\odot$), 8.6% of the total mass is in OB-type stars with masses between 10-120 $M_\odot$. Based on this we can extrapolate the above derived star-formation rate to a Galactic star-formation rate of $\frac{4.4 \pm 0.81}{8.6 \times 10^{-6}} = 2.44 \pm 0.81 M_\odot$ yr$^{-1}$. This estimate is based on the assumption that all the star-forming ATLASGAL sources form massive stars, which number is certainly contaminated with intermediate-mass nearby objects, and is at the same time also incomplete for the brightest sources saturated in both the MSX and WISE catalogs. Nevertheless, it provides an independent and comparable value for the global star-formation rate in our Galaxy derived by other methods. Using the YSO population revealed by Spitzer, Robitaille & Whitney (2010) suggest a value between 0.68 to 1.45 $M_\odot$ yr$^{-1}$, while Diehl et al. (2006) estimate $4 M_\odot$ yr$^{-1}$ based on radioactive $^{26}$Al measurements. Comparing these different tracers in a homogenous way Chomiuk & Povich (2011) arrive to an estimate of 2 $M_\odot$ yr$^{-1}$. Our estimate is consistent with these studies considering the large uncertainties in the exact number of clumps forming massive stars, the protostellar life-time estimates and the poorly constrained factor of multiplicity.

7.3. Formation time-scales

As discussed in Sect. 5.1 we expect our mid-IR characterization to be more robust against chance alignments compared to Contreras et al. (2013). Other studies, such as the BGPS, base the mid-IR diagnostics of their sources on the GLIMPSE and MSX point source catalogs. Dunham et al. (2011a) finds that 44% of the BOLOCAM sources have a mid-IR counterpart, however they consider a 50% chance alignment and arrive to a conservative estimate of 20% of the BGPS sources to have an embedded mid-IR source.

Our analysis (Sect. 5.1, 5.2) is based on requiring a detected source at 22 $\mu$m benefitting from a continuous sensitiv-
Table 2. Summary of cross-matches of dust condensations identified in the ATLASGAL survey.

| Catalogue | Matched sources | Fraction [%] |
|-----------|-----------------|--------------|
| MSX-ATLASGAL | 1609 | 16 |
| WISE-ATLASGAL | 3151 | 30 |
| MSX-WISE-ATLASGAL | 3483 | 33 |

Table 3. Mean and standard deviation of WISE colors of dust condensations.

| Sample   | [3.6]-[4.6] | [4.6]-[12] | [12]-[22] | [4.6]-[22] |
|----------|-------------|------------|----------|------------|
| AG-WISE  | 3.48±1.56  | 3.45±0.93  | 6.93±1.74 |
| CORNISH  | 3.34±2.35  | 2.89±1.94  | 6.23±3.94 |
| RMS      | 1.04±1.62  | 1.18±1.77  | 2.21±3.30 |
| MMB      | 1.51±1.86  | 2.31±2.37  | 3.82±3.78 |

1. We identify 10565 ATLASGAL sources in the main part of the survey, between $|l| < 60^\circ$ and $|b| < 1.5^\circ$. Galactic plane. In the extension region, between $-80^\circ < \ell < -60^\circ$ and $-2^\circ < b < 1^\circ$, with a higher average noise level we extract 296 sources. Our catalog is complete to >= 99% above 7$\sigma$.

2. We find good correlation in the distribution of peak flux density compared to the values from a different method by Contreras et al. (2013) which was optimized for larger size-scale sources corresponding to clumps and cloud structures. We derive a slope of $\alpha \sim 1.44 \pm 0.03$ for the distribution of the peak flux density, which is found to be consistent with other surveys, such as the BGPS.

3. We use the MSX and WISE point source catalogs to assess the star-formation activity of the ATLASGAL sources and find that 33% of them to harbor embedded mid-IR sources. Color-color plots of the WISE-ATLASGAL matches demonstrate the characteristic reddened colors of these sources.

4. The Galactic distribution of ATLASGAL sources shows peaks toward the most prominent star-forming complexes in our Galaxy. We find that the star-forming sources exhibit similar distribution and similarly peak at the position of rich complexes. Considering all WISE sources with characteristic red color we find a good correlation between the ATLASGAL clumps and red objects, suggesting that star-formation mainly takes place in large complexes.

5. We determine the Galactic scale-height for the dust sources of $\sim 0.32^\circ$, which is smaller than previous estimates using mid-IR surveys, however it is close to the value determined by surveys of young massive star-forming regions, e.g. using H$_2$O or methanol masers (Walsh et al. 2011; Urrutia et al. 2013).

6. From the fraction of star-forming sources we estimate a Galactic star-formation rate of $\sim 2.44 \pm 0.81$ $M_\odot$ yr$^{-1}$. Although this value is subject to large uncertainties due to the unknown factor of multiplicity, as well as the time-scale for the protostellar evolutionary phase, we still find a good agreement with other estimates based on various datasets.

7. Comparing the fraction of star-forming versus quiescent ATLASGAL sources, we show that the fraction of embedded sources exhibiting star-formation activity increases with the beam-averaged flux density. This ratio is found to be a rather constant value of 75% for 5 Jy beam averaged flux density, suggesting that the lifetime for the IR-dark evolutionary phase is short. We estimate an upper limit for the IR-dark phase of $7.5 \pm 2.5 \times 10^{4}$ years.

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8. Summary

We have produced a catalog of embedded sources in the ATLASGAL survey using a multi-scale decomposition tool to remove extended emission and then used a Gaussian source fitting algorithm (MRE-GCL, Motte et al. 2010). This method is optimized to identify the population of centrally condensed, compact structures. Here we summarize our main results:

- We identify 10565 ATLASGAL sources in the main part of the survey, between $|l| < 60^\circ$ and $|b| < 1.5^\circ$. Galactic plane. In the extension region, between $-80^\circ < \ell < -60^\circ$ and $-2^\circ < b < 1^\circ$, with a higher average noise level we extract 296 sources. Our catalog is complete to > 99% above 7$\sigma$.
- We find good correlation in the distribution of peak flux density compared to the values from a different method by Contreras et al. (2013) which was optimized for larger size-scale sources corresponding to clumps and cloud structures. We derive a slope of $\alpha \sim 1.44 \pm 0.03$ for the distribution of the peak flux density, which is found to be consistent with other surveys, such as the BGPS.
- We use the MSX and WISE point source catalogs to assess the star-formation activity of the ATLASGAL sources and find that 33% of them harbor embedded mid-IR sources. Color-color plots of the WISE-ATLASGAL matches demonstrate the characteristic reddened colors of these sources.
- The Galactic distribution of ATLASGAL sources shows peaks toward the most prominent star-forming complexes in our Galaxy. We find that the star-forming sources exhibit similar distribution and similarly peak at the position of rich complexes. Considering all WISE sources with characteristic red color we find a good correlation between the ATLASGAL clumps and red objects, suggesting that star-formation mainly takes place in large complexes.
- We determine the Galactic scale-height for the dust sources of $\sim 0.32^\circ$, which is smaller than previous estimates using mid-IR surveys, however it is close to the value determined by surveys of young massive star-forming regions, e.g. using H$_2$O or methanol masers (Walsh et al. 2011; Urrutia et al. 2013).
- From the fraction of star-forming sources we estimate a Galactic star-formation rate of $\sim 2.44 \pm 0.81$ $M_\odot$ yr$^{-1}$. Although this value is subject to large uncertainties due to the unknown factor of multiplicity, as well as the time-scale for the protostellar evolutionary phase, we still find a good agreement with other estimates based on various datasets.
- Comparing the fraction of star-forming versus quiescent ATLASGAL sources, we show that the fraction of embedded sources exhibiting star-formation activity increases with the beam-averaged flux density. This ratio is found to be a rather constant value of 75% for 5 Jy beam averaged flux density, suggesting that the lifetime for the IR-dark evolutionary phase is short. We estimate an upper limit for the IR-dark phase of $7.5 \pm 2.5 \times 10^{4}$ years.

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as 2D maps of dust emission. The reliability of the algorithm has been tested and discussed partly in Stutzki & Güsten (1990) and more in detail in Kramer et al. (1998). We refer the reader to these papers for a detailed discussion of the algorithm.

However, since this is the largest survey where Gaussclumps has been applied, we performed several test to assess the reliability of the detections. In Sect. A.1 we discuss the radial profiles of the sources and the impact of the filtering on the measured sizes, while in Sect. A.2 we compare the extracted peak fluxes to the original values in the filtered and non-filtered maps.

A.1. Sizes and radial flux density profiles

Since with the filtering some background emission is removed from the maps, we investigated the impact of this on the measured sizes by performing source extraction on maps with different scales of background emission removed. The change in the azimuthally averaged flux density profile by using different scales, between 50 – 400", for the background is illustrated in Fig. A.1. By comparing the extracted sizes in these measurements, we found that the decrease in the measured sizes with respect to that of the original maps is negligible (∼ 10% – 20%) for the 100" filtering scale used here.

A.2. Source parameters: the peak flux

We have performed several tests to estimate the reliability of the source parameters, such as peak flux density and size extracted by Gaussclumps. As a first step we compared the extracted peak fluxes with the fluxes in the filtered and the original maps. On average we find this difference to be less than 30% averaged on the individual tiles, however locally, in very complex regions this fraction can be higher. Fig. A.2 shows the ratio between the extracted and the measured peak flux density at the position of the source using the both the filtered and the original maps. The major fraction of the sources have peak flux density within 5% of the pixel values in the filtered maps confirming that the algorithm works good finding the peak position of the dust emission. On average the measured flux is 97.9% of the extracted value with a median of 98.2% (Fig. A.2).

The difference comes from two factors: first, fluctuations in the local noise may lead to small shift in the determined positions, i.e. determining the peak biased towards a higher value pixel instead of the peak of the Gaussian profile. Hence the measured value in the actual pixel may differ from the fitted value. We find ∼ 500 sources (5.4%) of the total sources where this flux ratio differs with >30% compared to unity. We inspected each of these sources and they are dominantly weak and large sources with no clear Gaussian distribution in which case the peak position is not well defined. On the other hand, since the algorithm decomposes sources in confused regions, we also find flux ratios below 100% which are blended sources. We find that a marginal fraction of the sources is actively deblended (0.34% of the total number of sources), where within the beam the source is decomposed into two components. There are, however a larger fraction (24%) of overlapping sources, which reflects the clumpy nature of the dust distribution in molecular clouds. Altogether we have a good census of the reliability of the extracted peak flux values of the algorithm.

The extracted peak flux densities compared to the values in the original emission maps show that the sources have on average 73.5% of the pixel value with a median of 78%. This suggests that the filtering lowers on average the peak flux values by 20-30%.

Appendix B: Color-color plots of star-forming ATLASGAL clumps

Figs. B.1-B.4 show color-color plots and a color-magnitude diagrams of the ATLASGAL and WISE matched sources. Comparing the positions of embedded UC-H II regions, RMS and MMB sources in Fig. B.3 we see that especially the former two occupy a well determined region with bright 12 µm flux and colors between 1.8 < [12]-[22] < 7. These sources correspond to evolved stages, H II regions and MYSOs. These two samples seem to have no distinguishable color properties.
Fig. A.1. One of the brightest sources detected shown with different scales of filtering, similarly as in Fig. 2. The peak flux of the object in this case decreases by 20% from the original images to the most compact one, while the size decreases by only 10%. Panel f) shows azimuthally averaged flux density profile with different scales of background emission removed. The green line corresponds to the filtering used for our catalog, which has $2\times50''$ as maximum scale. As a comparison a Gaussian profile is indicated in red dashed line with crosses and a dotted line with diamond symbols shows a power-law fit.

Fig. B.2. Color-color plots of ATLASGAL sources with a WISE source match (black dots). As a comparison, the colors of field stars from a test field are shown in gray dots.

Fig. B.3. Color-magnitude plots of ATLASGAL sources with a WISE source match (black dots). As a comparison, the colors of field stars from a test field are shown in gray dots.
Fig. B.4. Color-magnitude plots of ATLASGAL sources with a WISE source match (black dots). As a comparison, the colors of field stars from a test field are shown in gray dots.