

The APEX Telescope Large Area Survey of the Galaxy (ATLASGAL)

Frédéric Schuller¹
 Henrik Beuther²
 Sylvain Bontemps³
 Leonardo Bronfman⁴
 Philipp Carlhoff⁵
 Riccardo Cesaroni⁶
 Yanett Contreras⁴
 Tímea Csengari⁷
 Lise Deharveng⁸
 Guido Garay⁴
 Thomas Henning²
 Fabrice Herpin³
 Katharina Immer¹
 Bertrand Lefloch⁹
 Hendrik Linz²
 Diego Mardones⁴
 Karl Menten¹
 Vincent Minier⁷
 Sergio Molinari¹⁰
 Frédérique Motte⁷
 Quang Nguyen Luong⁷
 Lars-Åke Nyman¹¹
 Jill Rathborne⁴
 Vincent Reveret⁷
 Christophe Risacher¹²
 Delphine Russeil⁸
 Peter Schilke⁵
 Nicola Schneider⁷
 Jochen Tackenberg²
 Leonardo Testi¹³
 Tobias Troost¹
 Tatiana Vasyunina²
 Malcolm Walmsley⁶
 Marion Wienen¹
 Friedrich Wyrowski¹
 Annie Zavagno⁸

¹ Max-Planck-Institut für Radioastronomie, Bonn, Germany

² Max-Planck-Institut für Astronomie, Heidelberg, Germany

³ Laboratoire d'Astrophysique de Bordeaux, France

⁴ Universidad de Chile, Santiago, Chile

⁵ University of Cologne, Germany

⁶ Osservatorio Astrofisico di Arcetri, Firenze, Italy

⁷ IRFU/SAP, Commissariat à l'énergie atomique, Saclay, France

⁸ Laboratoire d'Astrophysique de Marseille, France

⁹ Laboratoire d'Astrophysique de l'Observatoire de Grenoble, France

¹⁰ INAF–Istituto di Fisica dello Spazio Interplanetario, Roma, Italy

¹¹ ALMA, Santiago, Chile

¹² SRON, Groningen, Netherlands

¹³ ESO

Thermal emission from dust at submillimetre wavelengths is a direct tracer of high column densities and, thus, of dense cloud regions in which new stars are forming. Surveys of the Galactic Plane in thermal dust emission have the potential to deliver an unbiased view of high-mass star formation throughout the Milky Way. The Atacama Pathfinder Experiment (APEX) telescope is ideally located for mapping the inner Galaxy. Using the Large APEX Bolometer Camera (LABOCA), we have recently completed the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL). This survey, which covers 360 square degrees at 870 μm , provides the first unbiased sample of cold dusty clumps in the Galaxy at submillimetre wavelengths and reveals the clumpy structure of the cold interstellar medium over very large scales that have previously been little explored.

Trying to understand the early stages of star formation is an important topic of modern astrophysics. While significant progress has been achieved in the field of low-mass star formation, both from theoretical and observational aspects, the quest for the earliest phases of massive star formation remains a major challenge. The prime reason for this is the short lifetime of massive stars, which makes them rare, so that most high-mass star-forming regions are located at distances greater than 1 kpc. Therefore, systematic surveys on the scale of the full Galaxy are required to provide large samples of massive pre- and proto-stellar objects.

The advent of large arrays of bolometers has made it possible to map large areas in the sky at submillimetre (sub-mm) and millimetre (mm) wavelengths. Using the Max-Planck Millimeter Bolometer (MAMBO) array at the IRAM 30-metre telescope, Motte et al. (2007) obtained a complete 3 by 2 degree map covering the Cygnus-X complex at 1.2 mm. They could derive statistically significant results and lifetimes for the evolutionary phases of high-mass star formation. In particular, no high-mass analogue of pre-stellar dense cores was found by this study, implying a very short lifetime for the earliest phases of dense cores in

which high-mass stars are being formed. Whether this is representative can only be revealed by an unbiased survey of the complete Galactic Plane, providing large samples, which will allow us to place far stronger constraints on the early stages of high-mass star formation.

Located at one of the driest sites on Earth, and at a latitude of -23° , the 12-metre diameter APEX telescope (Güsten et al., 2006) is ideally located to observe the inner two quadrants of the Galactic Plane. Equipped with the 295-pixel LABOCA instrument (Siringo et al., 2007; Siringo et al., 2009), APEX can map hundreds of square degrees at 870 μm in reasonable time. Making the best possible use of this “mapping machine”, a consortium involving the Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn, the Max-Planck-Institut für Astronomie in Heidelberg, the ESO community and the Universidad de Chile has embarked on the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL). The LABOCA observations have just been completed, covering 360 square degrees of the inner Galactic Plane. Several follow-up projects have already been started.

The first systematic survey of the inner Galactic Plane in the submillimetre range

In the past decade, several bolometer arrays have been used by various teams to map individual star-forming complexes. For example, Johnstone et al. (2004) used SCUBA to map the Ophiuchus and Perseus clouds, and Enoch et al. (2006) covered Perseus, Ophiuchus and Serpens with BOLOCAM. Unlike these targeted observations, the ATLASGAL project aims at mapping the entire Galactic Plane accessible from APEX at 870 μm . A similar survey of the northern Galactic Plane has recently been completed with BOLOCAM at the Caltech Submillimeter Observatory (CSO) at 1.1 mm (Rosolowsky et al., 2010). Only such blind surveys have the potential to deliver unbiased samples of cold dusty cores.

The ATLASGAL observations started in 2007. A large programme was conducted in 2008–9, using observing time from MPIfR, from ESO and from Chile. The

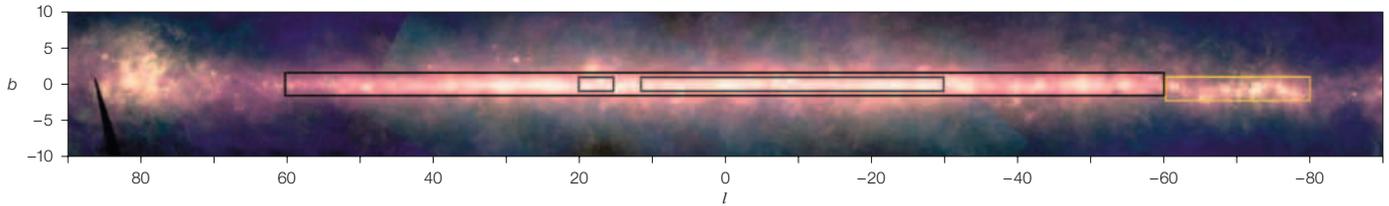


Figure 1. The coverage of the ATLASGAL observations is shown in Galactic coordinates (l, b) in degrees, on top of an IRAS false-colour image (blue: 12 μm , green: 60 μm , red: 100 μm). The large black frame shows the 360 sq. degrees mapped to date; the smaller frames inside the larger one show the data obtained in 2007 and presented in Schuller et al. (2009). The frame in yellow delineates the additional region being mapped in 2010.

current data cover the $\pm 60^\circ$ range in Galactic longitude, over $\pm 1.5^\circ$ in latitude (see Figure 1). To complete the coverage of the most active regions in the inner Galaxy, another small programme was accepted in 2010. Observations of the -80° to -60° range in longitude are still ongoing.

The telescope patterns are linear on-the-fly maps, where the telescope scans at (typically) 3 arcminute/s along a line, and the step between lines is 1.5 arcminutes. The 11-arcminute field of view and 295 pixels of LABOCA ensure a high redundancy in a single map. In addition, each position in the sky is covered by at least two different maps, observed with different scanning angles. More details on the observing strategy and data reduction can be found in Schuller et al. (2009). The noise level in the final maps is usually around 50 mJy/beam. Assuming a dust temperature of 15 K and typical properties for dust, this

corresponds to a 5σ detection of individual clumps of $10 M_\odot$ at 2 kpc, and $100 M_\odot$ at the distance to the Galactic Centre.

Compact sources and long filaments

The LABOCA maps reveal thousands of compact sources, as well as extended objects, many of them showing filamentary structures. Such filaments have a width of just a few parsecs, and can extend over 100 pc. A typical example is shown in Figure 2.

With a spatial resolution of 19 arcseconds, the LABOCA data can spatially resolve objects with sizes of 0.3 pc and larger, for typical distances of 3 kpc or more. Most of the compact objects are actually resolved by our observations, with full width at half maximum generally of order 30 arcseconds. This corresponds to massive clumps, which will probably give birth to groups or clusters of stars: most clumps have total gas+dust masses of a few $100 M_\odot$, and the most extreme have a few $10^4 M_\odot$. Only with interferometers that provide a resolution of order 1 arcsecond is it possible to resolve such clumps into individual star-forming cores (today, for example with the Plateau de Bure interferometer, e.g., Beuther et al., 2007, and in the future with the Atacama

Large Millimeter/submillimeter Array, ALMA).

Many of these compact sources are embedded in extended emission on the arcminute scale, as can be seen in the close-up examples in Figure 3. Our 5σ sensitivity of 0.25 Jy/beam corresponds to a hydrogen column density of order 10^{22} cm^{-2} , or, to a visual extinction of about 10 magnitudes. We note that, due to the subtraction of correlated noise during data reduction, uniform emission on scales larger than 2.5 arcminutes is filtered out and is not present in the final maps (more details are given in Schuller et al., 2009). Observations in the sub-mm continuum are nevertheless complementary to the infrared extinction techniques, which are sensitive to larger scales, but “saturate” in the densest regions.

The long filaments seem sometimes to connect large molecular complexes together (e.g., near the M16 nebula, see Figure 4), or to trace the boundaries of supergiant bubbles.

Nature of the sources

Because thermal emission from dust in the submillimetre range is optically thin, the emission seen with LABOCA directly

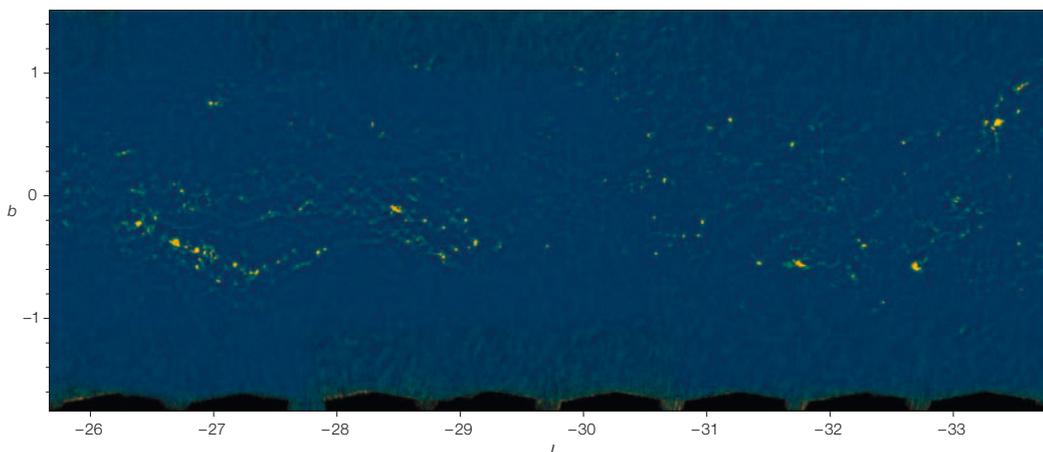
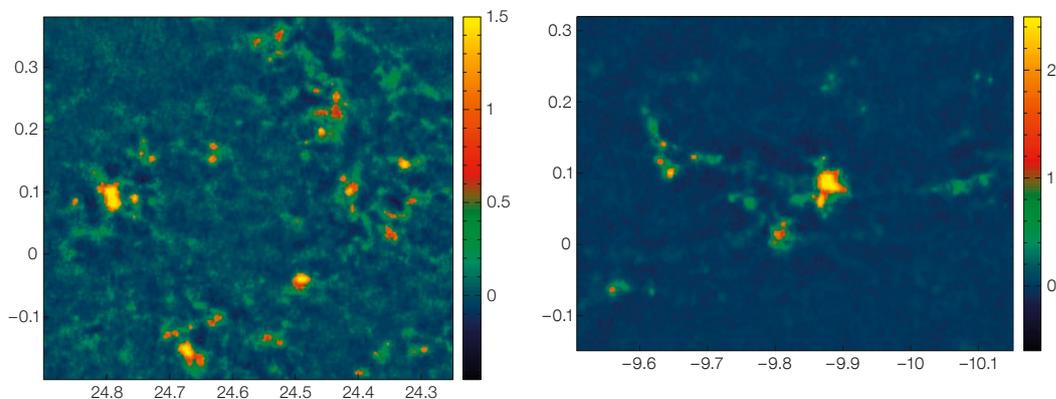


Figure 2. Example ATLASGAL map at 870 μm , in the direction of the Norma arm, showing about 20 square degrees, or 6% of the surveyed area (in Galactic coordinates). Compact objects and filamentary structures are prominent.

Figure 3. Close-up views of representative regions, towards Galactic longitudes $+24.6^\circ$ (left) and -10° (right). The intensity scale (in Jy/beam) is linear, as shown on the right of each panel. Galactic coordinates (l, b) shown in degrees.



scales with the amount of matter along the line of sight. Therefore, our survey is primarily sensitive to massive star-forming clumps. We cannot exclude, however, that some of our compact sources are nearby low-mass clumps (our 5σ detection limit corresponds to a one solar mass clump at a distance of 1 kpc). Evolved stars, such as post-asymptotic giant branch (AGB) or supergiant stars, also have large amounts of dust in their envelopes and can therefore appear bright at $870\ \mu\text{m}$. However, only a few sources are unresolved in our maps, and could correspond to evolved stars.

During their early evolution, star-forming clumps increase in temperature, as the protostar starts to warm the inner part of the clump. The peak of the thermal emission then moves from the sub-mm to the far- and mid-infrared. We have systematically searched for infrared counterparts to our compact sources in the Infra-Red Astronomical Satellite (IRAS) and the Mid-course Space Experiment (MSX) point-source catalogues. Only about 10% of ATLASGAL sources could be associated with mid- and far-infrared IRAS sources, and one third have a counterpart within a 30-arcsecond search radius in the MSX mid-IR database (Figure 5).

Sources with infrared counterparts are relatively warm, and correspond to later stages of star formation, when one or several protostar(s) have already been formed, and a molecular hot core or a compact H II region has developed. On the other hand, the majority of ATLASGAL sources have no bright IR counterpart (they may however be detected at $24\ \mu\text{m}$ with the superior sensitivity of the Spitzer surveys). These sources are likely to be

very cold, and to represent the earliest stages of massive star formation, and, in particular, the pre-stellar phase.

A first version of the ATLASGAL catalogue of compact sources will soon be published (Contreras et al., in preparation). Associations with IRAS and MSX point sources will be included. This catalogue will allow the distribution of massive star-forming clumps in the inner Galactic Plane to be studied in a systematic way for the first time. The catalogue will later be cross-associated with databases at other wavelengths, e.g., the Spitzer GLIMPSE and MIPS GAL surveys, and with the Herschel Hi-GAL data when they become available.

Star formation triggered by expanding H II regions

The Spitzer–GLIMPSE images at $8\ \mu\text{m}$ have unveiled a “bubbling Galactic disc”. More than 600 bubbles with diameters of a few arcminutes have been catalogued by Churchwell et al. (2006, 2007). As shown by Deharveng et al. (2010), more than 85% of these $8\ \mu\text{m}$ bubbles enclose H II regions and contain hot dust emitting at $24\ \mu\text{m}$. Taking advantage of the simple morphology of these bubbles, Deharveng et al. (2010) used ATLASGAL to search for dense neutral shells and condensations surrounding the H II regions. A sample of one hundred bubbles from the Churchwell et al. (2006) catalogue was studied. Among the 65 regions for which the angular resolution of the ATLASGAL observations is high enough, they find that 40% of the bubbles are surrounded by cold dust (accumulated at their borders during the expansion of the central

H II region); another 28% contain condensations clearly interacting with the ionised gas. Thirteen bubbles exhibit ultra-compact H II regions associated with the dust condensations found adjacent to their ionisation fronts. Another five show 6.7 GHz methanol masers, tracers of very young embedded high-mass proto-stars, in similar condensations.

The conclusion from this study is that more than a quarter of the bubbles could have triggered the formation of massive objects. Star formation triggered by H II regions has long been thought to be an important process, especially for the formation of massive stars, but so far little systematic evidence was available. We now plan to use complementary data to characterise the properties (such as mass and evolutionary stage) of the young sources formed on the borders of these regions.

Follow-up projects

Based on a preliminary extraction of the compact sources, several follow-up projects in spectral lines have been started. In particular, observations of the inversion lines of ammonia (NH_3) with the Effelsberg radio telescope for the northern sources, and with the Parkes telescope for the south, provide the most efficient way to measure radial velocities and to derive kinematic distances. These lines of NH_3 also provide rotation temperatures, which give an estimate of the gas temperature in the clumps. So far, more than 1000 sources have been observed in NH_3 (Wienen et al., in preparation). These observations show that the compact sources are not randomly distrib-

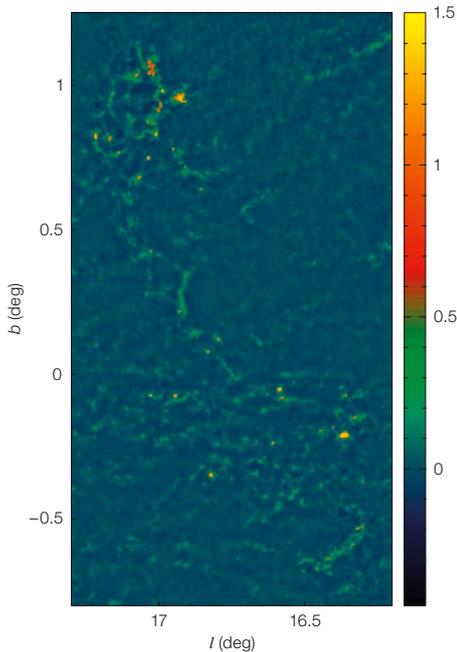


Figure 4. Example ATLASGAL map in the vicinity of the M16 (Eagle) nebula. The intensity scale is linear, as shown on the right, in Jy/beam.

uted at all possible distances, but they are rather found to gather within coherent complexes, at a given distance. Such complexes extend over several hundreds of parsecs.

We have also observed a large sample of over 600 sources at 3 mm with the Australian Mopra telescope. This telescope, equipped with an 8 GHz wide spectrometer, allows many molecules to be detected simultaneously (e.g., SiO, N₂H⁺, HCN, HCO⁺, NH₂D, ...), tracing a broad range of physical conditions. Such a large dataset also provides valuable information on the chemical processes occurring within the sources. A detailed analysis of these data is in progress (Wyrowski et al., in preparation). A smaller sample was also observed in the 1 mm window with the APEX telescope. These observations are highly complementary to the Mopra data, since they allow us to observe, at a similar spatial resolution, higher energy transitions of the same molecules.

Since maser emission is known to be another good tracer of massive star formation, we have started to follow up a

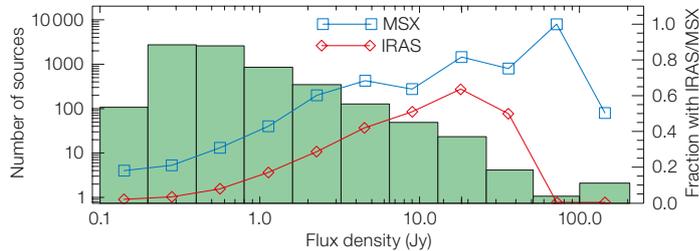


Figure 5. Distribution of peak fluxes from a preliminary extraction of 6000 ATLASGAL compact sources. The fraction of sources in each bin for which a counterpart in the IRAS or MSX catalogues could be found is shown in red or blue, respectively.

large sample of bright ATLASGAL sources in the H₂O maser line at 22 GHz, with the Effelsberg 100-metre radio telescope. In 2009, we observed 140 sources, and water maser emission, tracing outflow activity, was detected in about two thirds of the sources, including many new detections.

Finally, we have observed a sample of about 100 bright sources at 350 μ m, using the Submillimeter APEX Bolometer Camera, SABOCA (Siringo et al., 2010). The combination of LABOCA and SABOCA data allows us to compute the dust spectral index. This is found to vary between ~ 2 and values above 4, which could trace an evolution of the dust properties. Moreover, the spatial resolution of APEX at 350 μ m is 7 arcseconds, significantly better than that of LABOCA. Therefore, the SABOCA data make it possible to study the fragmentation of star-forming cores. These observations took place in May 2010, and a detailed analysis is ongoing (Troost et al., in preparation). We are also planning to use the SABOCA instrument to map large regions of the Galactic Plane, in order to study core fragmentation and dust properties on large scales, mostly unexplored so far.

Perspectives: a long-lasting legacy database

The SABOCA and LABOCA data, when combined with the available Spitzer GLIMPSE and MIPS GAL surveys at 3.6 to 24 μ m, provide spectral energy distributions (SEDs) for a very large sample of sources, from the near-IR to the sub-mm range.

Currently, the Herschel Space Observatory is mapping the same area of the Galactic Plane as observed for ATLASGAL in the wavelength range from 70 to 500 μ m, as part of the Hi-GAL project

(Molinari et al., 2010). We plan to combine the Hi-GAL and ATLASGAL data, in order to build SEDs for thousands of compact Galactic sources. Using also the Spitzer data, we will then obtain complete SEDs from 3.6 μ m to 870 μ m. This dataset will remain unique for many years to come. The catalogue of compact sources with identifications at other wavelengths will be available to the public upon completion, as well as the reduced calibrated maps. We also plan to include results from follow-up observations in this public database. This will give a high legacy value to the survey, providing well characterised samples of targets for many possible studies.

Last but not least, the first ALMA antennas should be available soon for early science. This will be the perfect time for conducting follow-up studies of carefully selected samples at an unprecedented spatial resolution. The ATLASGAL catalogue will provide ALMA with several thousand compact sources, including hot cores, high-mass proto-stellar objects, and cold pre-stellar cores. Thus ATLASGAL is expected to trigger numerous follow-up studies with ALMA, aimed at characterising the physical conditions and the chemistry of the massive star formation process at the smallest possible scales.

References

- Beuther, H. et al. 2007, A&A, 466, 1065
- Churchwell, E. et al. 2006, ApJ, 649, 759
- Churchwell, E. et al. 2007, ApJ, 670, 428
- Deharveng, L. et al. 2010, A&A, accepted, arXiv:1008.0926
- Güsten, R. et al. 2006, A&A, 454, L13
- Enoch, M. L. et al. 2006, ApJ, 638, 293
- Johnstone, D. et al. 2004, ApJ, 611, L45
- Molinari, S. et al. 2010, A&A, 518, L100
- Motte, F. et al. 2007, A&A, 476, 1243
- Rosolowsky, E. et al. 2010, ApJS, 188, 123
- Schuller, F. et al. 2009, A&A, 504, 415
- Siringo, G. et al. 2007, The Messenger, 129, 2
- Siringo, G. et al. 2009, A&A, 497, 945
- Siringo, G. et al. 2010, The Messenger, 139, 20