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An Era Comes to an End: The Legacy of LABOCA at APEX

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It was 13 years ago, in May 2007, when the Large APEX Bolometer Camera (LABOCA) was commissioned as a facility instrument on the APEX telescope at the 5100-m-high Llano de Chajnantor. This 870-μm bolometer camera, in combination with the high efficiency of APEX and the excellent atmospheric transmission at the site, has offered an unprecedented capability in mapping the submillimetre continuum emission in objects ranging from the Solar System and star-forming regions throughout the Galactic plane, to the most distant galaxies. As the operation of LABOCA is soon coming to an end to make space for a new array of continuum detectors, we present an overview of the challenges, lessons learned and science impact that it has generated. To date, LABOCA has produced the most papers of any APEX instrument and compares favourably with many VLT instruments.

Introduction

Continuum imaging at (sub)millimetre wavelengths provides unique information on the thermal dust emission from circumstellar discs (for example, Beckwith et al., 1990) and star-forming regions (for example, Motte, Andre & Neri, 1998). As these wavelengths probe the steep Rayleigh-Jeans slope of cold (< 100 K) dust emission, the observed flux density remains roughly similar from z = 1 to z = 10, which makes this wavelength regime ideal to select targets over half the age of the Universe. As the sensitivity depends on the bandwidth covered, bolometers have a major advantage over heterodyne instruments. After initial efforts using single bolometers (for example, Kreysa, 1985), several small arrays of bolometers came online in the 1990s: Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) in Hawai'i (Holland et al., 1999), Max Planck Millimeter BOlometer (MAMBO) on the IRAM 30-m telescope of Pico Veleta and SEST IMager Bolometer Array (SIMBA) on the SEST at La Silla in Chile (both Kreysa et al., 1999).

In the 1990s, SCUBA had just opened up the field of observational submillimetre cosmology by mapping massive clusters and the Hubble Deep Field (Smail et al., 1997; Hughes et al., 1998). Its main limitation was the small field of view and further progress was only possible by increasing the bolometer array sizes by an order of magnitude. This motivated the bolometer development group led by Ernst Kreysa at the Max Planck Institute for Radio Astronomy in Bonn (MPIfR), who had already provided the community with MAMBO, SIMBA and its line of predecessors, to build LABOCA (Siringo et al., 2009) for the new Atacama Pathfinder Experiment (APEX) 12-m submillimetre telescope as one of its main facility instruments (Güsten et al., 2006). With as many as 295 bolometers covering a circular field of 11.4 arcminutes, LABOCA would remain the largest submillimetre array till the SCUBA-2 instrument became available on the JCMT in 2012 (Holland et al., 2013). Being installed on APEX, LABOCA could also make optimal use of the excellent weather conditions on Chajnantor, where the 870-μm atmospheric window is observable for almost two-thirds of the available weather conditions (Otarola et al., 2019). In addition, seeing the same sky as ALMA optimised LABOCA's synergy as the ideal source finder for ALMA.

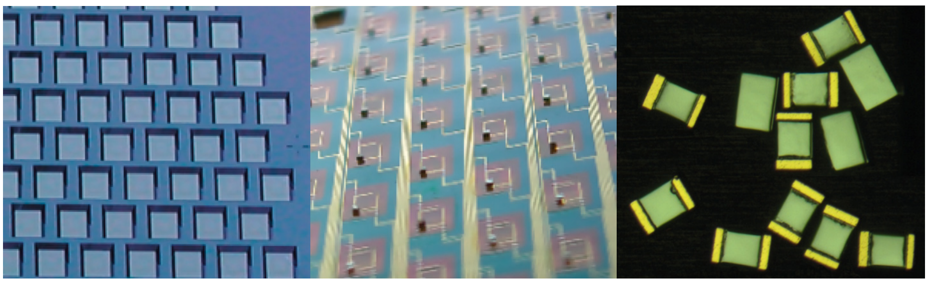


Figure 1. The LABOCA bolometer array consists of 295 semiconducting composite bolometers arranged in a hexagonal grid. The array is manufactured on a 10-cm single-crystal silicon wafer coated on both sides with a silicon-nitride film by thermal chemical vapour deposition. The wiring is created by microlithography of niobium and gold thin layers (left); one broken membrane is visible on the top left corner. On the opposite side of the wafer, 295 square cavities are etched into the silicon wafer by wet etching with potassium hydroxide, producing freestanding, unstructured silicon-nitride membranes of 400-nm thickness (middle). A very thin titanium layer is then sputtered onto the cavity side of the wafer to act as absorber for the submillimetre radiation. In a last step the thermistors are soldered to free-standing membranes with an indium alloy. The thermistors are brick shaped (right) but appear as small cubes on the membranes because of the viewing angle.

Figure 2. The image on the left shows APEX staff astronomer, Andreas Lundgren, in the process of refilling LABOCA. The transfer tube that is wrapped behind his back goes from a liquid helium dewar in the foreground to the helium tank in LABOCA, shown in the inset image in the upper left corner. The cryostat is shown from above in this inset. The image on the right shows Ernst Kreysa, the leader of the MPIfR bolometer group, together with the LABOCA cryostat in the Cassegrain cabin of the APEX telescope. At the time the picture was taken, the instrument PolKa was being installed.

Being faster than the sky

Observations of astronomical objects from ground-based telescopes at (sub)millimetre wavelengths require techniques to minimise disturbance from the Earth's atmosphere, which is seen by a bolometer as a fluctuating bright screen. The most widely used minimisation technique is to modulate the signal from the sky, usually by chopping with the secondary mirror between two close positions, ideally at a frequency higher than that of the sky fluctuations. Synchronous demodulation is then used to filter out the sky noise and extract the signal of astronomical interest. Mapping a region of the sky by scanning in the chopping direction will result in both a positive and a negative source signal separated by the chopping amplitude. A similar technique has been used with double horn receivers at centimetre wavelengths. Efficient algorithms have been developed to retrieve sources from double-beam maps (Emerson, Klein & Haslam, 1979). This method has also been used with bolometers.

The experience with MAMBO and SIMBA played an important role in the design of LABOCA. The new bolometer camera was intended from the beginning to be used in a fast scanning mode, to take full advantage of the fast-moving telescope (as an ALMA prototype) without using the chopping secondary. The design therefore required fast sampling of the bolometers' signals. Following the success of the MAMBO analogue-to-digital converter (ADC)-based backend, a new ABBA backend for LABOCA has been built, upgrading the scheme of the MAMBO one, which can sample up to 320 analogue channels in parallel up to 1000 Hz (see a detailed description by Siringo et al., 2009). The total power design has been optimised to make LABOCA capable of mapping the most diffuse emission of large extended sources. A detailed analysis of spatial filtering with an investigation of the Chamaeleon dark clouds by Belloche et al. (2011a,b) showed that the size of the structures that can be recovered is limited to about 5 arcminutes, i.e., half the array size.

During the commissioning of LABOCA, extensive tests and simulations were undertaken to determine the optimal scanning pattern. Lissajous patterns are often used at other (sub)millimetre telescopes to achieve good spatial sampling. However, they turned out to have a tendency to give greater weight to the edges of the map with less coverage in the centre. A new observing pattern was therefore created for fast scanning with APEX: by using strokes at constant velocity in polar coordinates it was possible to move the telescope along spiral patterns optimised to obtain maps with full spatial sampling and excellent coverage. For coverage of square degrees or more, rectangular on-the-fly maps turned out to be more efficient.

The lack of a readily available software package to reduce the data has been recognised as a major drawback of the fast scanning technique applied to MAMBO and SIMBA. For this reason, in parallel with the hardware development of LABOCA, a new data reduction software package was developed, called the Bolometer data Analysis package (BoA; Schuller, 2012), which is able to reduce data acquired with LABOCA in any of the possible observing modes; the package is mostly based on Python, and is open source, distributed under the GNU General Public License. In addition, the Comprehensive Reduction Utility for SHARC-2 package (CRUSH; Kovács, 2008) was adapted to handle LABOCA data.

The LABOCA detectors

The initial design of LABOCA considered using superconducting transition-edge sensors (TES) developed at the MPIfR in collaboration with the Institute for Photonics Technology of Jena (IPHT) and operated with a closed-cycle pulse-tube cryo-cooler (Jethava et al., 2008). However, the pressure to install LABOCA as quickly as possible led to the decision to stick with well-established semiconductor-based bolometers (neutron transmutation doped [NTD]-germanium thermistors, see below) in a liquid helium cooled "wet" cryostat to avoid problems with microphonics. While this inevitably led to some operational constraints (see the section on cryogenics below), it did allow

LABOCA to produce scientific results several years before other submillimetre instruments like Herschel and SCUBA-2 came online. The effort in designing and prototyping TES bolometers was not in vain: the new technology was used in the Submillimetre APEX Bolometer Camera, SABOCA (Siringo et al., 2010), a 37-element array for the 350-μm atmospheric window that was commissioned in 2008 as a facility instrument on APEX. SABOCA remained operational until 2015, when it was replaced by the ArTéMiS instrument covering both the 350- and 450-μm atmospheric windows (Talvard et al., 2018).

NTD thermistors for bolometer arrays need extremely tight control of the doping for uniform performance. The group under Eugene E. Haller at Lawrence Berkeley Laboratory (LBL) pioneered the use of NTD-germanium for this purpose, in cooperation with the MPIfR bolometer group (Palaio et al., 1983). When designing LABOCA, several crystals of NTD-Ge with different dopings were available to choose from. Optimal chip resistance is then determined only by temperature and geometry to match the noise properties of the silicon field-effect transistor amplifier. This was achieved by precision dicing at LBL, with boron low-noise contacts and gold coating for ease of soldering. The chips are finally polish-etched to remove noise producing surface states, which explains the rounded corners of the chips (Figure 1).

Tertiary optics with integrated polarimetry mode

The main task of the tertiary optics is to transport the beams from the Cassegrain focal plane to the final focal plane in the cryostat, while changing the focal ratio from *f*/8 to *f*/1.5. In order to satisfy the boundary conditions of the APEX C-Cabin, an optical solution was found with two Gaussian beam telescopes in series. This design has an ideal position for a reasonably sized reflective half-wave plate with a small angle of incidence near the common waist of the two telescopes. Three off-axis mirrors, two plane mirrors and a lens (the cryostat window) make up the tertiary optics. Unfolding the optical path at the plane mirrors would show that this solution still maintains one plane of symmetry. This property contributes to the diffraction-limited performance at 350 μm. Relaxing the wavelength to 870 μm and doing without the polarimetry mode would allow much simpler optics to be designed.

The polarimeter for LABOCA is an enhanced version of the Polarimeter für Bolometer Kameras (PolKa) developed at MPIfR between 2000 and 2004 as a plug-in instrument adding polarisation capabilities to any of the MPIfR bolometer arrays, at different wavelengths and on different telescopes (the 10-m Heinrich Hertz Telescope and the IRAM 30-m telescope). A complete description and some results are presented in Siringo et al. (2012).

The polarisation modulator used in PolKa is a rotating reflection-type half-wave plate. The reflection-type half-wave plate consists essentially of two parts: a wire-grid linear polariser and a plane mirror, held parallel to each other. By tuning the distance between the two parts, it is possible to introduce a controlled phase shift between the two components of the linear polarisation, because one is reflected by the wires and the other one by the mirror after a longer path.

PolKa for LABOCA was not yet available at the time of LABOCA's installation and commissioning — it was installed at the

Figure 3. LABOCA emission map of the Barnard 211/213 filament in Taurus (red emission) superposed on an optical DSS image of this region (background). Note the rich substructure shown by the LABOCA emission along this region, including multiple branches and condensations corresponding to dozens of small-scale fibres inside this filament.

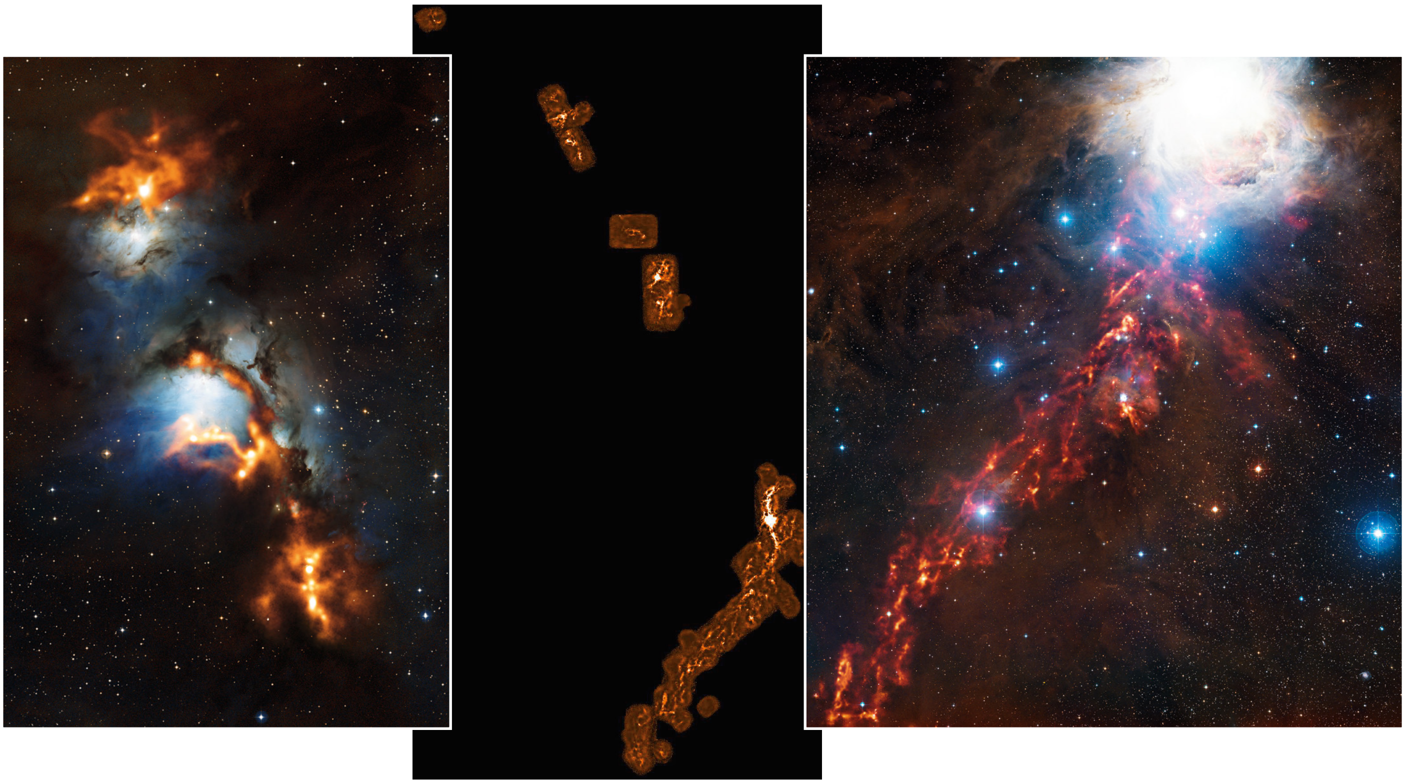


Figure 4. Middle: full extent of the Orion LABOCA survey, spanning almost 11 degrees north to south. The northern half covers prominent star-forming clumps in the Orion B giant molecular cloud (from north to south: L1622, NGC 2071 and NGC 2068, Ori B9, and NGC 2024 and NGC 2023 including the Horsehead Nebula). The southern half covers a major fraction of the Orion A giant molecular cloud, including the Integral-Shaped Filament with the Orion Nebula at its centre at the top, and the L1641 cloud further south. Left: zoom-in on the NGC 2071 and NGC 2068 area, with LABOCA dust emission shown in orange on top of a multicolour optical image (DSS). Right: close-up of the filamentary dust emission extending south-east of the Orion Nebula in the L1641 cloud.

end of 2009 as a permanent add-on available for use with LABOCA until the end of its operation. For polarimetry, one mirror was replaced by the reflection-type half-wave plate on its air bearing. When PolKa was not being used, only the delicate wire grid of the reflection-type half-wave plate had to be removed (Figure 1). A filter wheel, holding two polarisation filters and a calibration hot load, has replaced the original hot load in front of the cryostat window. No other modifications of the optics were required. In order to avoid mechanical or optically induced microphonics, the reflection-type half-wave plate is rotated on an air bearing.

Photometric mode

As LABOCA is a sparsely sampled array, a given source is seen by a single bolometer for only ~ 1/16th of the observing time for a Nyquist sampled map. After the wobbler became available, a more efficient photometric mode was offered to the community as a means of determining flux densities of compact sources without spatial information, but with high sensitivity. This was done by using the APEX wobbler to chop symmetrically between the target and nearby off positions in a similar way as is done for heterodyne observations. For the LABOCA implementation, the key was to use a sensitive bolometer on the optical axis[a] to stare at the target source, while the other elements produced redundancy in estimating the sky emission. This was a good way of integrating deeper in compact regions but this mode still required an exquisitely stable atmosphere and was prone to systematic errors such as spillover of ground radiation as a result of imperfections in the secondary mirror surface. While this photometric mode was quite popular from 2010 to 2013, it lost its relevance for compact point sources as ALMA could reach better sensitivity significantly faster than LABOCA. This mode was therefore decommissioned in August 2016.

Working with cryogenics at 5100 m

The safe handling of cryogenic liquids at 5100 m was one of the challenges in the operation of LABOCA. Thanks to strict procedures, this went fine apart from a small mishap when nitrogen was accidentally put into the helium tank. This required quick action to melt the nitrogen ice with a copper rod in order to avoid over-pressurising the helium tank. But even in regular operation, doing a daily refill of helium at 5100 m is quite a strain on operations. Everyone at APEX will remember the heroic “LABOCA rescue missions” involving a 130-km ride to the high site in the middle of a freezing night to top up liquid helium on the (thankfully rare) occasions when LABOCA unexpectedly ran out of coolant. All new APEX instruments after LABOCA have been designed to run with closed-cycle cryostats that can be fully remotely operated. One lesson learned from LABOCA was to mount the cryostat inside the moving Cassegrain cabin at an angle close to 45 degrees so that it is close to vertical during the observations. This is particularly important during the condensation phase of the recycling process. During the two hours of LABOCA recycling, we therefore restrict the elevation range of the observations with any other instrument between elevations of 30 and 60 degrees. Although this puts quite some constraints on the observing schedule, the APEX science operations staff have been able to successfully integrate these recycling restrictions into the observing plans. This applies to all closed-cycle cryostats based on pulse-tubes operating in the Cassegrain cabin.

Science highlights

The range of science targets observed during the 13 years of LABOCA operations is very wide. In the Solar System many asteroids were observed, including a time-coordinated campaign with Herschel and Planck to determine their variability and suitability as calibrators. Within our Galaxy, LABOCA observed debris discs, envelopes around stars, massive stars and even the entire Galactic plane observable from Chajnantor under the APEX Telescope Large Area Survey of the GALaxy (ATLASGAL). In extragalactic astronomy, LABOCA contributed to the study of dust in nearby galaxies, and galaxy clusters using the Sunyaev Zel'dovich effect. At high redshift, LABOCA made optimal use of the aforementioned fact that the flux of an object remains roughly identical from z = 0.7 to 10 to study radio galaxies, dusty star-forming galaxies and protoclusters. As it is impossible to cover all topics, we here present only a few selected highlights which illustrate the high synergy with other observatories, mainly ALMA but also Herschel and the VLT.

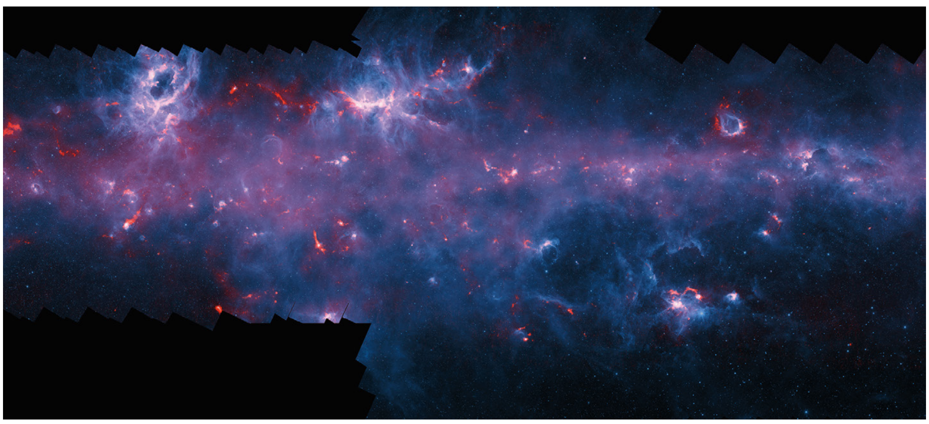


Figure 5. A subsection of the 870-µm ATLASGAL data shows up in red, while the background blue image is from the Spitzer Space Telescope as part of the 3.6-µm Galactic Legacy Infrared Mid-Plane Survey Extraordinaire. The fainter extended red structures come from complementary observations made by the Planck satellite.

Star-forming filament in Taurus

Characterising the origin of stars inside filaments is recognised as one of the major open questions in the field of star formation. The cosmic dust grains in these filaments are so cold that observations at submillimetre wavelengths by the LABOCA camera at APEX are needed to detect their faint glow. In order to better understand this process, Hacar et al. (2013) used LABOCA to study the Barnard 211/213 region in Taurus, a prototypical star-forming filament for this type of study.

The iconic LABOCA map of the Barnard 211/213 region (Figure 3) exemplifies the complex interplay between cloud structure and the origin of stars. In this image, two newborn stars are recognisable as bright spots highlighted by the glowing warm dust around them. A series of additional starless condensations indicate the presence of dense cores on the verge of collapsing to form yet more stars. Connecting these cores and stars, LABOCA also detects the fainter dust emission of the cloud extending over more than 10 light-years. For the first time, the enhanced sensitivity of this LABOCA image, comparable in quality to similar space observations obtained by Herschel, revealed the internal structure of this paradigmatic filament. In a pioneering discovery, the combination of this LABOCA image with additional molecular line observations demonstrated the existence of dozens of small-scale sub-filaments, known as fibres, bundled together in space and forming an elongated structure on large scales.

Cold dust present in star-forming regions

LABOCA is well suited to measuring the amount of cold dust present in star-forming regions, with a spatial resolution which corresponds well to the typical sizes of nearby protostellar envelopes (~ 10 000 au). The Orion A and B giant molecular clouds have been studied most extensively, with a total coverage of 5.2 square degrees. This includes the Orion Nebula region with the famous "Integral Shaped Filament", the L1641 cloud to its south, and NGC2023, NGC2024, Ori B9, NGC2068, NGC2071 and L1622 in the Orion B cloud. Data reduction was optimised to recover as much of the extended emission as possible (it tends to be filtered out by sky-noise removal), while maintaining excellent sensitivity in the compact sources. Figure 4 shows an overview of the entire survey area in the middle, and two close-ups of NGC 2071/2068 and the Orion A giant molecular cloud.

Together with more targeted, smaller-field SABOCA mapping, the LABOCA Orion survey data provided submillimetre photometry for more than 300 protostar candidates, identified from Spitzer thermal infrared imaging. These data were essential in determining the reservoir of gas that is still available in the protostars' cold envelopes for accretion onto their central star and disc. Together with a Herschel survey using the Photodetector Array Camera and Spectrometer (PACS) at 70, 100, and 16 µm — the Herschel Orion Protostar Survey (HOPS) — spectral energy distributions were obtained over the full infrared to submillimetre regime (Furlan et al., 2016); this included a sample of protostars that were actually too cold to be detected by Spitzer, which were found serendipitously in the Herschel maps (Stutz et al., 2013) and included in the LABOCA wide-field maps. This

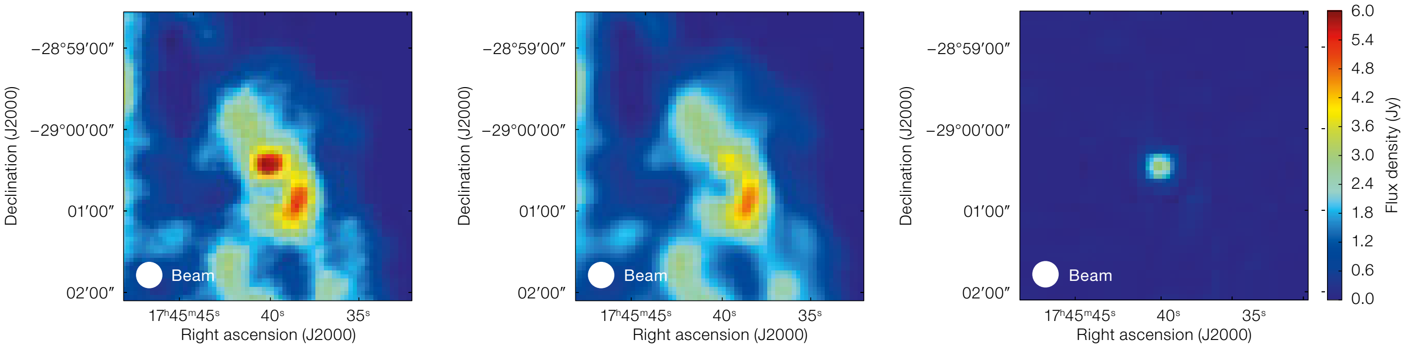


Figure 6. Data reduction process for the LABOCA campaigns. All maps show the innermost 3.5 × 3.5 arcminutes. Left: a single measurement map of the Galactic centre from a typical observation. Centre: model of the extended submillimetre emission from the Galactic centre: co-added maps with subtracted point source at the position of SgrA*. Right: remaining map after subtracting the model from the data. The point-like source represents the submillimetre emission from SgrA* itself (Subroweit et al., 2017).

arguably makes HOPS protostars the largest and best characterised protostar sample in a single star-forming region (Fischer et al., 2017).

ATLASGAL

The ATLASGAL survey (Schuller et al., 2009) is the single most successful APEX large programme with nearly 160 associated science papers[1] receiving over 4600 citations. The legacy of this survey will continue, thanks to the reduced data products publicly available through ESO Phase 3 data[2], catalogue release[3] and the ATLASGAL Database Server[4]. The ATLASGAL maps cover an area of sky 140 degrees long and 3 degrees wide. ATLASGAL complements observations from ESA's Planck and Herschel satellites. The combination of the Planck and APEX data allowed astronomers to add information on the diffuse emission across the survey area and to estimate the fraction of dense gas in the inner Galaxy (Csengeri et al., 2016). The ATLASGAL data were also used to create a complete census of cold and massive clouds where new generations of stars are forming.

The ATLASGAL project has led to a sustained flow of follow-up projects using ALMA and many other telescopes. The catalogue of compact clumps extracted from the ATLASGAL images was recognised as the best, least biased, and most representative database from which to extract a suitable sample for follow-up spectroscopic observations in molecular lines to characterise the physical and chemical conditions of dense molecular clumps associated with high-mass star formation over a wide range of evolutionary states (Foster et al., 2011). This catalogue was also ideal for drawing up a sample of massive dense clumps for high-spatial-resolution (down to 0.06 pc) follow-up observations with ALMA (Csengeri et al., 2017). The Search for high-mass Protostars with ALMA Revealed up to Kiloparsec Scales project (SPARKS) is now delivering its first results. Finally, by complementing the ATLASGAL data with spectroscopic observations to derive distances and with existing infrared surveys, Urquhart et al. (2018) could draw a detailed picture of the changes in physical properties (temperature, luminosity, onset of star formation) during the early evolution of high-mass protostars and proto-clusters. These results are based on a complete sample of ~ 8000 dense clumps, the largest sample of submillimetre dense clumps with reliable distance estimates to date.

Time-domain science

One of the strengths of APEX is its considerable scheduling flexibility, which makes it optimal for monitoring campaigns. LABOCA has observed several

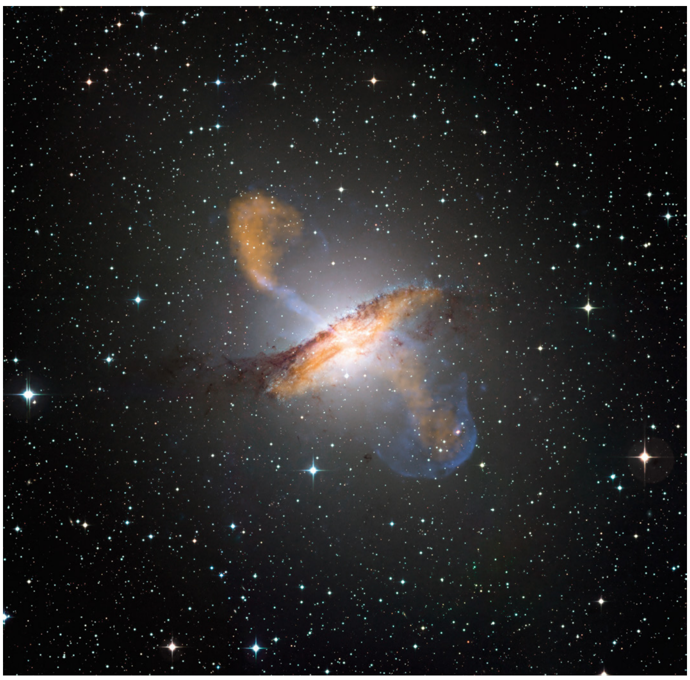


Figure 7. This image shows a colour composite image of the radio galaxy NGC 5128, aka Centaurus A, revealing the lobes and jets emanating from the active galaxy's central black hole. This is a composite of images obtained with three instruments, operating at 870 μm (LABOCA: orange), in X-rays (Chandra X-ray Observatory: blue) and in visible light (Wide Field Imager [WFI] on the MPG/ESO 2.2-m telescope at La Silla); it shows the stars and the galaxy's characteristic dust lane in close to "true colour".

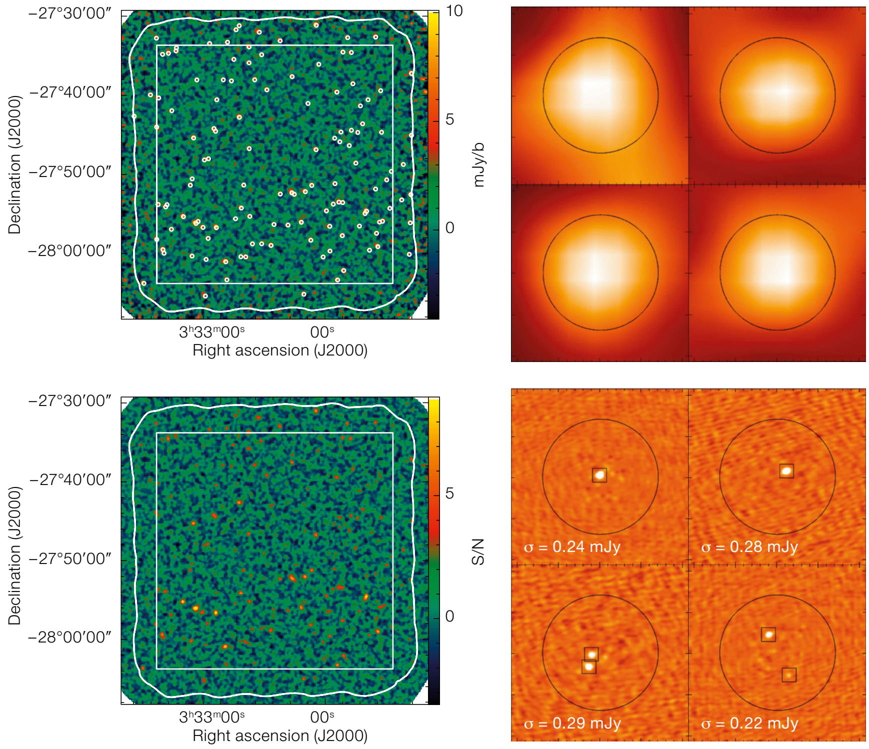


Figure 8. The image on the left shows the LABOCA map of the ECDFS with 122 sources detected (Weiß et al., 2009). This map illustrates the source-finding capabilities of LABOCA, which allowed deeper and higher-resolution ALMA follow-up observations (see the 44 x 44-arcsecond images on the right, from Hodge et al., 2013 and Karim et al., 2013).

classes of objects that show significant variability in their submillimetre continuum, such as gamma-ray bursts (for example, de Ugarte Postigo et al., 2012), blazars (Fuhrmann et al., 2014) and supermassive black holes.

The Galactic centre was monitored over eight epochs between 2008 and 2014 in a coordinated campaign with the NAOS–CONICA instrument (NACO) on ESO's VLT. The data show observational evidence that, together with theoretical modelling, supports the idea that the SgrA* synchrotron flare spectra are optically thin in the near-infrared and peak in the 350-GHz range (Eckart et al., 2012 and references therein; see Figure 6). Subroweit et al. (2017) performed a statistical analysis of the variable 100- and 345-GHz flux densities of Sgr A* and find that both flare flux density distributions are well described by power laws with an index around 4. Using a plasmon model to explain the flares one can constrain the important model parameters: the initial synchrotron turnover frequency of the flare source components and their expansion velocity is mostly above 100 GHz and below a velocity value of 0.01 *c* (Eckart et al., 2012).

Time-domain science carried out by Dharmawardena et al. (2020) using LABOCA archival data of Betelgeuse, in combination with more recent SCUBA-2 data, showed that its submillimetre luminosity has dimmed by about 20% during its optical minimum.

Nearby active galaxies

In the 1970s, the first observations of the (sub)millimetre continuum emission in nearby galaxies showed the importance of this wavelength regime for studying optically thin emission from cold dust in galaxies and the variability of synchrotron emission in active galactic nuclei (for example, Hildebrand et al., 1977; Elias et al., 1978). It took about another decade of technology development until the first (sub)millimetre maps of nearby starburst galaxies became available which showed the distribution of gas and its relation to the nuclear activity in infrared-bright systems such as M82 and NGC253 (Krugel et al., 1990). LABOCA, with its large field of view and high sensitivity submillimetre maps, was finally sensitive enough to also study the cold dust in the discs of nearby galaxies, which are often ~ 20–30 times fainter than active nuclear regions but carry comparable amounts of dust.

Figure 7 shows one of the first high-fidelity LABOCA images of Centaurus A (Weiß et al., 2008) combined with optical data taken with the MPG/ESO 2.2-m telescope and X-ray data observed with Chandra (Kraft et al., 2000). It reveals not only emission from cold dust associated with the prominent dust absorption lanes, but also the synchrotron emission from the radio jets emerging from the accreting supermassive black hole at the centre of Centaurus A. The LABOCA observations show that material in the jet is travelling at about half the speed of light. This image has become a textbook example in journals and the media to illustrate high-energy phenomena in galaxies.

LABOCA ECDFS Submillimetre Survey

The flagship extragalactic project during the first years of LABOCA was a deep survey of the Extended Chandra Deep Field South (ECDFS), producing 34 papers which have received more than 3000 citations. Such a survey was foreseen in the science justification of APEX itself. An investment of 320 hours of the best weather conditions (precipitable water vapour, PWV < 1 mm) effectively monopolised this range in Local Sidereal Time for the first two years of LABOCA operations, but the yield was enormous. The LABOCA ECDFS Submillimetre Survey (LESS; Weiß et al., 2009; Smail, Walter & LESS Consortium, 2009) was the largest uniform extragalactic survey of its time, covering a region the size of the full Moon. The final map, shown in Figure 8, is available from the ESO Phase 3 interface[5]. The observing mode and data reduction procedures developed for LESS have become the standard for all deep extragalactic mapping projects with LABOCA. On the science side, the LESS map set a new standard — the follow-up of the 120 sources in the map was the foundation for one of the highest-impact projects when ALMA entered operations in

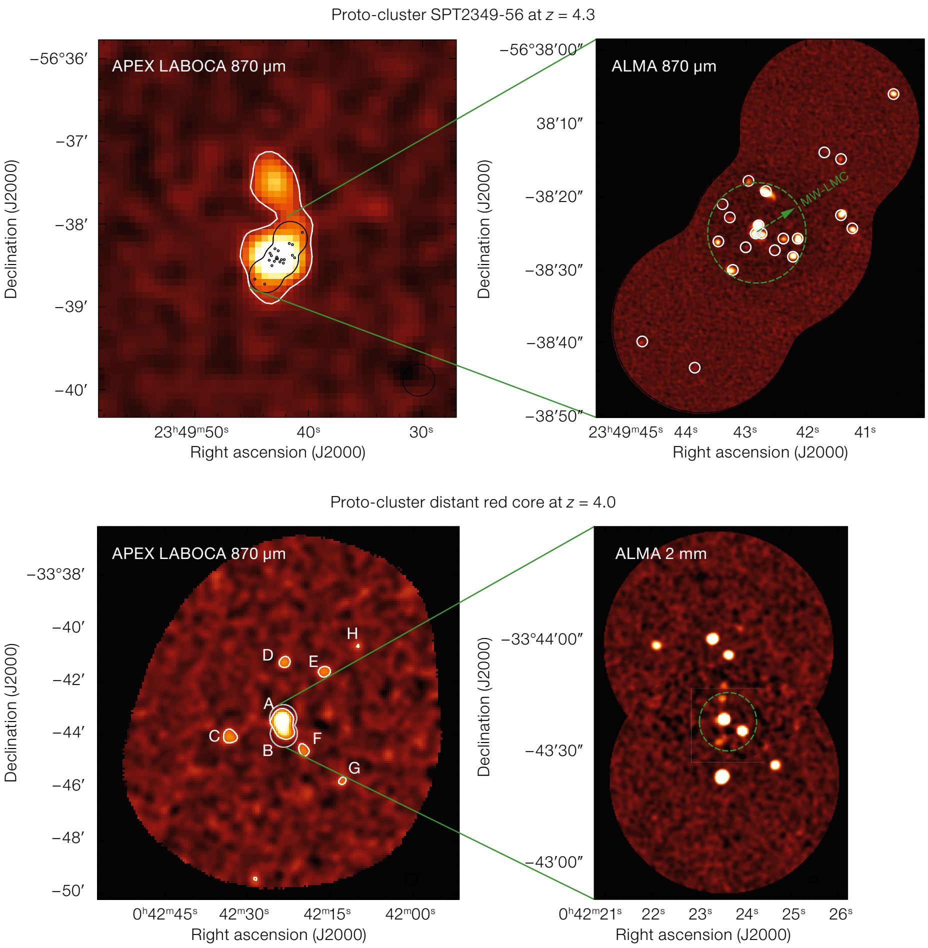


Figure 9. Top: LABOCA 870-μm image of the SPT 2349-56 system at redshift z = 4.304 overlaid with the ALMA coverage towards the southern LABOCA source (black contour; the white contour is the 4σ LABOCA signal-to-noise ratio; Miller et al., 2018). At top right is the ALMA 3 pointing mosaic of the high-spatial-resolution 870-μm continuum emission underlying the [CII] emission line that identifies 21 individual galaxies as members of this protocluster. The core of the protocluster contains 15 (Ultra) Luminous InfraRed Galaxies, (U)LIRGs, with a projected separation equal to the MW–LMC distance only (dotted green circle). Additional ALMA data show that the northern LABOCA source is also part of this system (Hill et al., 2020). Bottom: same presentation for the distant red core at z = 4.002 with the ALMA footprint shown as grey contour. The ALMA 2-mm continuum shows that the distant red core consists of 10 (U)LIRGs at the same redshift. In addition to the protocluster core the LABOCA image reveals an overdensity of submillimetre galaxies (SMGs) in the vicinity of the distant red core that may also be part of this structure (Oteo et al. 2018; Lewis et al. 2018; Ivison et al., 2020).

2012 (Swinbank et al., 2012). Imaging the LESS sources at much higher spatial resolution was one of the first projects undertaken when ALMA entered science operations (Hodge et al., 2013). The redshift determination and study of the properties of the 120 LESS sources are still ongoing using the VLT, ALMA (Danielson et al., 2017; Wardlow et al., 2018) and soon using the JWST. It took SCUBA-2 at the JCMT over a decade to cover an area 10 times wider than LESS to comparable depth, while ALMA's largest areas are < 10% those of LESS.

Gravitationally lensed dusty star-forming galaxies

One of the most unexpected discoveries made with LABOCA happened in May 2009, while observing a lensed z = 3 galaxy called the "Cosmic Eye". While the source remained undetected, the observation showed a bright 100-mJy source about 1 arcminute away. The observer (one of the authors of this paper) first suspected this was due to an error in the pointing model because of a recent intervention. However, further investigation revealed that it coincided with another triple-lensed system. A quick follow-up with the Green Bank Telescope determined a redshift of z = 2.3 for this source, the first time this was done using a blind CO search. This system, magnified ~ 32 times, was dubbed the "Cosmic Eyelash" because of its shape and proximity to the Cosmic Eye (Swinbank et al., 2010). It provided, thanks to a string of DDT proposals, a first insight into the kinematics, chemistry and interstellar medium properties of a high-redshift star-forming galaxy at the spatial resolution and signal-to-noise which would take another 5+ years for ALMA to match. At the time of discovery, the Cosmic Eyelash was the only high-redshift source sufficiently bright to use to commission instruments aboard Herschel.

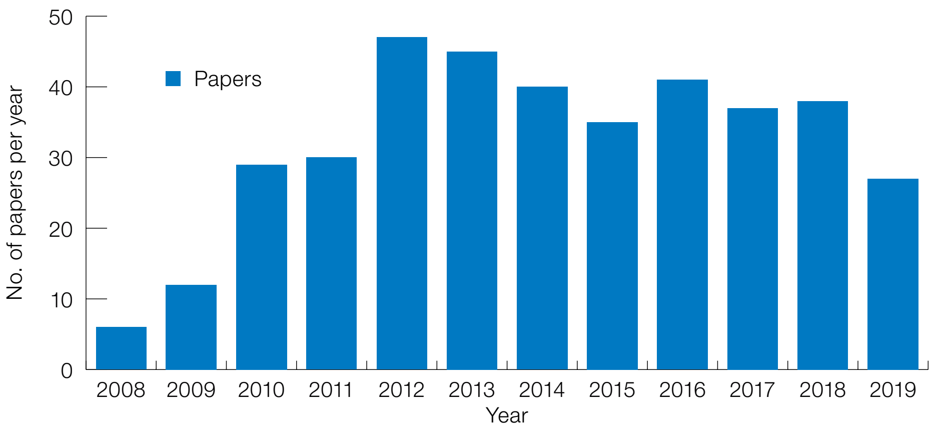
This chance discovery was possible thanks to LABOCA's wide field of view and it became the prototype of the population of lensed submillimetre galaxies. These distant objects can be studied in unprecedented detail thanks to the gravitational magnification that boosts the total intensity and allows their intrinsic structure to be resolved.

While the Cosmic Eyelash was a chance discovery, LABOCA would soon start playing a crucial role in a systematic search and characterisation of this population of lensed dusty star-forming galaxies selected using wide-field surveys with the Herschel Space Observatory and the South Pole Telescope (SPT). The high sensitivity and sharper spatial resolution of LABOCA were critical to providing complementary 870-μm photometry and separating them into point-like strongly lensed high-redshift galaxies and protoclusters which are typically spatially extended with LABOCA. LABOCA enabled the discovery of the most distant objects in both of these categories (Strandet et al., 2017; Miller et al., 2018; and Oteo et al., 2018).

LABOCA in numbers

A total of 596 LABOCA proposals have been approved for scheduling by the proposal committees in Sweden, Chile, MPIfR and ESO, of which 327 are associated with data[b]. Based upon one or more

Figure 10. The number of papers published per year between 2008 and 2019 in refereed journals based on data obtained with LABOCA.



of these data sets, 387 papers have been published between 2008 and 2019, which corresponds to an average of 32 papers per year.

Over the years, LABOCA has been observing for 9300 hours (193 000 scans), out of which 7900 hours were scans of a scientific nature (on, raster, and on-the-fly mapping [otf]) and 1400 hours were of calibration-type nature (point, go, focus, cal, and skydip). About 70% of the scans were observed with pwv < 1 mm. It should be pointed out that the observing time includes instrument setup and telescope movement time, so the true on source time is lower than this number.

LABOCA has (so far) been cooled down approximately 47 times at APEX. In total the cryostat has been kept cold for a total of 1893 days, i.e., more than 5 years. In order to achieve this, the contents of 82 250-l liquid helium dewars have been consumed (an estimated total of 20 500 l). Given that 387 LABOCA papers have been published using a total of 9300 hours, each paper corresponded to a consumption of 53 l of liquid helium, or 2.2 l per hour. This number will decrease with time as more papers continue to be published after LABOCA is decommissioned.

Beyond LABOCA

LABOCA turned out to be one of the most robust APEX instruments and it has outlived its originally expected lifetime (for example, the ABBA computer is still working after 15 years!). Its space in the Cassegrain cabin will now be taken by the CarbON CII line in post-rEionization and ReionizaTiOn epoch project (CONCERTO), which will add a spectral domain to wide-field bolometer imaging (The CONCERTO collaboration et al., 2020). However, as a pioneering wide-field submillimetre camera in the southern hemisphere, LABOCA leaves a data archive with a legacy value that will certainly lead to a further growth in the number of LABOCA papers in the future.

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Links

[1] ESO Telescope Bibliography: http://telbib.eso.org/
[2] ATLASGAL ESO Phase 3 data query form: http://archive.eso.org/wdb/wdb/adp/phase3_main/form?phase3_collection=ATLASGAL&release_tag=1
[3] ATLASGAL catalogue release: https://www.eso.org/qi/catalog/show/67
[4] ATLASGAL database server: https://atlasgal.mpifr-bonn.mpg.de/cgi-bin/ATLASGAL_DATABASE.cgi
[5] LESS ESO Phase 3 data query form: http://archive.eso.org/wdb/wdb/adp/phase3_main/form?phase3_collection=LESS&release_tag=1

Notes

[a] Ideally, one would use pairs or triples of bolometers to spend even more time on source, but moving away from the optical axis introduced too many uncertainties.
[b] The reasons for the discrepancy are that some projects were not (yet) observed, and in some cases the data are associated with another project code (i.e., when a proposal is resubmitted to different periods and/or when a proposal is submitted to more than one partner).