A New Era in Submillimetre Continuum Astronomy has Begun: LABOCA Starts Operation on APEX

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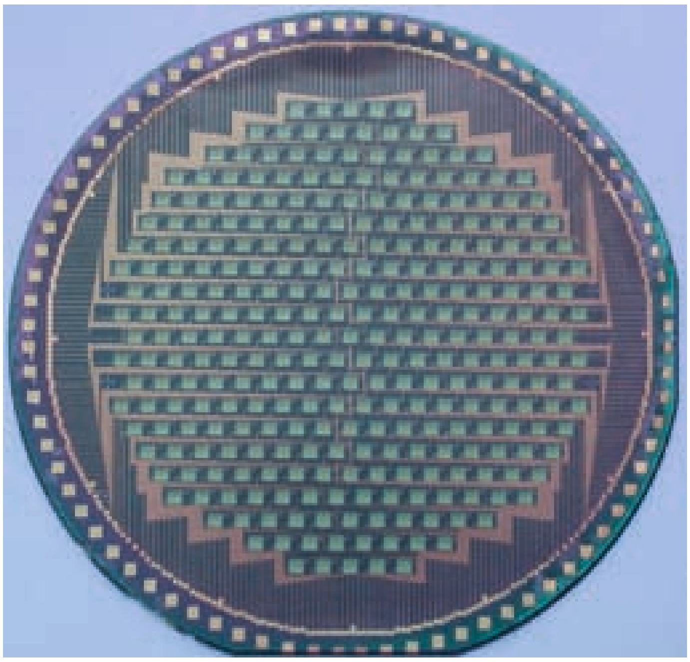

Figure 1: A 'naked' LABOCA silicon wafer. Each small square is a bolometer.

In May 2007, the Large APEX Bolometer Camera LABOCA was commissioned as a facility instrument on the APEX 12-m submillimetre telescope located at an altitude of 5100 m in northern Chile. The new 870-μm bolometer camera, in combination with the high efficiency of APEX and the excellent atmospheric transmission at the site, offers unprecedented capability in mapping submillimetre continuum emission. An overview of LABOCA and the prospects for science are presented.

A technological challenge

A new facility instrument has started operation on the APEX telescope (Atacama Pathfinder Experiment, Güsten et al., 2006) as a collaborative effort between the Max-Planck-Institut für Radioastronomie in Bonn (MPIfR), ESO and the Onsala Space Observatory (OSO). The new Large APEX BOlometer CAmera (LABOCA) is an array of bolometers designed for fast mapping of large sky areas at high angular resolution and with high sensitivity: a challenging task. Developed by the Bolometer Group of the MPIfR, LABOCA is the most complex system ever developed by this group. The design of this new facility takes advantage of the experience accumulated over several years in developing bolometers for millimetric and submillimetric atmospheric windows and operating them on ground-based telescopes.

The main obstacle, when observing at millimetre and submillimetre wavelengths, is our Earth's atmosphere, which is seen by a bolometer like a bright screen. It is as difficult as trying to do astronomical observations in the optical during daytime. This is largely due to the water vapour present in the atmosphere, with only small contributions from other components, like ozone. In the submillimetre range the only sources in the sky brighter than the atmosphere are the planets Venus, Mars, Jupiter and Saturn (and, of course, the Sun and the Moon). All other celestial objects have weaker fluxes, usually orders of magnitude weaker than the atmospheric emission. Besides, the atmosphere is not stable and the amount of water vapour along the line of sight can change quickly, giving rise to instabilities of emission and transmission, called 'sky noise'.

Observations of astronomical objects from ground-based telescopes have to pierce that screen presented by the atmosphere, therefore requiring techniques to minimise its effects. The most widely-used technique is application of a switching device, usually a chopping secondary mirror (commonly called a 'wobbler'), to observe alternatively the source and an area of blank sky close by, at a frequency higher than the variability of the sky noise. Invented for observations with single pixel detectors, this method is also used with arrays of bolometers. However, it presents some disadvantages and the most evident are, among others, that the wobbler is usually slow (1 or 2 Hz), posing a limitation to the scanning speed, and that not all telescopes are equipped with a wobbler.

LABOCA has been specifically designed to work without a wobbler to remove the atmospheric contribution, using a different technique which well suits observations with an array of detectors. This technique, called 'fast scanning' (Reichertz et al. 2001), is based on the idea that, when observing with an array, each unit bolometer looks at a different part of the sky and chopping is no longer needed. A modulation of the signal is produced by moving the telescope across the source field of interest. The atmospheric contribution (as well as part of the instrumental noise) will be strongly correlated in all bolometers and a post-detection analysis of the correlation across the array will allow extraction of the signals of astronomical interest from the atmospheric foregrounds. The post-detection bandwidth is defined by the beam size and by the scanning speed; relatively high scanning speeds are ideal. This technique was first tested by the MPIfR bolometer group in 2000 with the MAMBO (Max-Planck Millimetre Bolometer, Kreysa et al. 1999) array of 37 bolometers, installed on the IRAM 30-m telescope (Instituto de Radioastronomía Milimétrica, Pico Veleta, Spain; Baars et al. 1987). The same technique was extensively used in the following years for observations with the SIMBA (SEST Imaging Bolometer Array, Nyman et al. 2001) bolometer array on the SEST (Swedish-ESO Submillimetre Telescope, La Silla, Chile; Booth et al. 1989) telescope, which is not equipped with a chopping secondary mirror.

The experience with MAMBO and SIMBA has been essential for the design of LABOCA, which represents the evolution to a receiver specifically optimised for the fast scanning technique. Challenging technological choices have been implemented in its design. The most evident is the large number of pixels (nominally 295, see Figure 1), making the correlation removal extremely efficient. Another point is the large post-detection bandwidth. SIMBA was built following the same design scheme as MAMBO: that is both receivers are optimised for the differential technique with a wobbler, and a high-pass filter is used to cut off frequencies below the chopping frequency. LABOCA, instead, is a true total power system (without high-pass filtering) with a large stable post-detection bandwidth, extending down to 0.1 Hz. Moreover the reduction of the data acquired in fast scanning requires the use of special algorithms (Weferling et al. 2002) and the lack of a software package ready to reduce the data was the major drawback of the fast scanning technique applied to MAMBO and SIMBA. For this reason, in parallel with the hardware development of LABOCA, completely new software was developed, the Bolometer Data Analysis package (BoA, Schuller et al., in prep.), which is able to reduce data acquired with LABOCA in any of the possible observing modes.

Figure 2: LABOCA in the Cassegrain cabin of the APEX telescope. The receiver is in the centre of the picture. Four of the five mirrors used for the optical coupling are visible.

APEX is the ideal telescope for using the fast scanning technique as it can move extremely fast and its control software allows new observing patterns which fit well to the fast scanning technique. The 5100 metre high site on Llano de Chajnantor, where APEX is located, on the one hand can make the maintenance of the system uncomfortable, but on the other hand provides excellent atmospheric conditions for most of the year.

Technical overview

The detector array of LABOCA is micromachined on a 4-inch (102-mm) silicon wafer where unstructured silicon nitride membranes carry the composite bolometers. The membranes are only 0.4 µm thick and are coated with a thin titanium film which absorbs the incoming radiation. Neutron-transmutation-doped (NTD) germanium chips (called thermistors), soldered to the membranes, detect the temperature rise due to the absorption of the radiation. The array is mounted inside a cryostat, which uses liquid nitrogen and liquid helium for thermal shielding and pre-cooling of the array. A closed-cycle double-stage sorption cooler is then used to reach a stable operation temperature of 0.285 K. The cryostat is mounted in the Cassegrain cabin of the telescope (see Figure 2) and the optical coupling to the main telescope beam is provided by a series of metal mirrors and a lens placed at the cryostat entrance. A set of cold filters, mounted on the liquid nitrogen and liquid helium shields, define the spectral passband, centred at a wavelength of 870 µm (345 GHz) and about 150 µm (60 GHz) wide (see Figure 3). A monolithic array of conical horn antennas, placed in front of the bolometer wafer, collects the radiation onto the bolometers. One LABOCA beam is 18.6 arcseconds wide (full width at half maximum, FWHM) and the field of view (FoV) of the complete array covers 11.4 arcminutes. The array undersamples the sky, with a distance of two beams between adjacent pixels

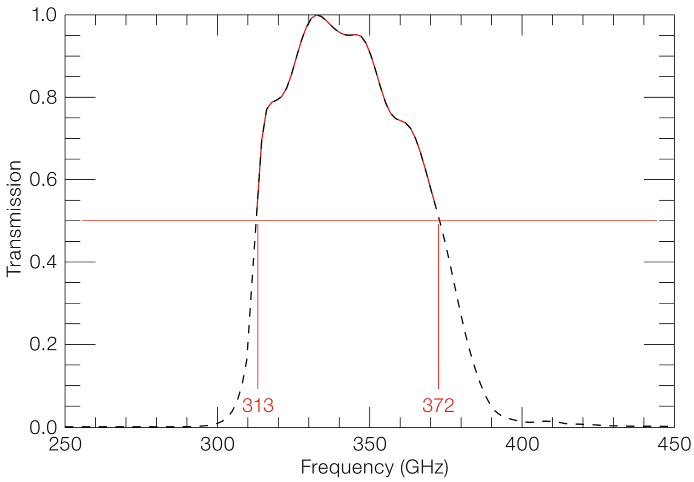

Figure 3: Spectral response of LABOCA. The central frequency is 345 GHz and the 50 % transmission is between 313 and 372 GHz.

(see Figure 4). The voltages at the edges of the thermistors are channelled to the outside of the cryostat along 12 flat cables (made of manganin wires on kapton substrate) going through low-noise, unity gain JFET amplifiers heat sinked to the liquid nitrogen bath. Upon exiting the cryostat, the signals pass to room-temperature low-noise amplifiers and electronics. The 295 signals are distributed to four identical, custom made, amplification units, providing 80 channels each for a total of 320 available channels. The extra 25 channels are used for technical purposes like noise monitoring and calibrations. The amplification units are equipped with microprocessors providing a digital interface, accessible remotely via the local network, to control some of their properties, like the amplification gain which can be set in the range 270–17 280.

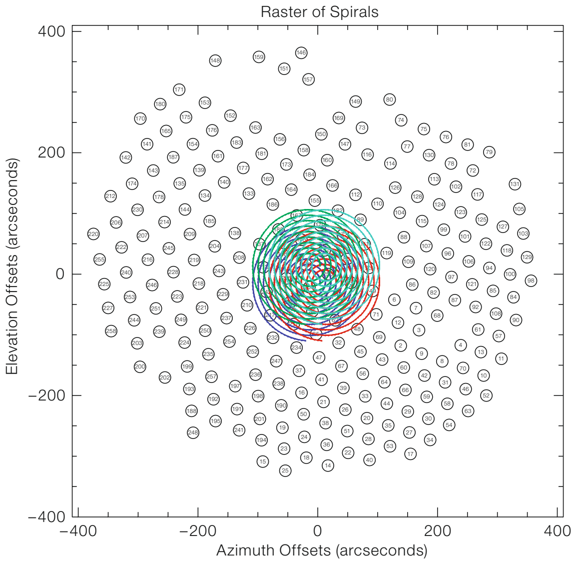

Figure 4: The coloured lines show the scanning pattern of a single bolometer for a four-point raster of spirals. The circles show the measured positions and sizes on sky of all the functional LABOCA detectors.

At the beginning of each observation, the DC offset is removed from each channel to avoid the risk of saturation. The values of the 320 removed offsets are temporarily stored in a local memory and, at the end of the observation, are written in the corresponding data file, to be used during the data-reduction process. The 320 channels are digitized over 16 bits by four multifunction DAQ PCI boards mounted in an industrial computer. The data-acquisition software provides an interface to the APEX control software, used to set up the hardware, and a TCP data server, for the data output. The amplification units provide an AC current to bias the bolometers and perform real-time demodulation of the 320 signals. This electronic scheme is fundamental for the stability of the post-detection signals at low frequencies. The AC bias frequency is provided by the data acquisition system as a submultiple of the sampling frequency (usually set to 1 kHz) thus synchronising the bias to the data sampling. Before reaching the telescope's control software, the data (about 4 MB/s) are digitally filtered and downsampled to 25–50 Hz in real time by a computer specifically equipped for bridging between data-acquisition and control software. Another computer is devoted to monitoring and control of most of the electronics embedded in the receiver (e.g. monitoring of all the temperature stages, control of the sorption cooler, calibration unit, etc.) and also provides an interface to the APEX control software, allowing remote operation of the system.

Observing modes and performance on the sky

In order to reach the best signal-to-noise ratio using the fast scanning technique with LABOCA, the frequencies of the signal produced by scanning across the source need to match the white noise part of the post-detection frequency band (0.1–20 Hz), mostly above the frequencies of the atmospheric fluctuation. The maximum telescope scanning speed for LABOCA is limited by the time resolution of the position information given by the APEX control system, that is about 4 arcminutes/s. The minimum scanning speed required for a sufficient source modulation depends on the atmospheric stability and on the source structure and is typically about 3 arcseconds/s.

The APEX control system currently supports two basic scanning modes: on-the-fly (OTF) maps and spiral scanning patterns. OTF scans are rectangular scanning patterns, with a constant scanning speed, in horizontal or equatorial coordinates. The OTF pattern is typically used to map sky areas much larger than the FoV of LABOCA (i.e. greater than 30 arcminutes). For compact objects, or pointing and flux calibrations, the spiral scanning pattern provides the faster method to obtain a fully sampled coverage of the FoV of LABOCA at the required scanning speed. In this mode the telescope scans with a constant angular speed along a spiral, in horizontal or equatorial coordinates. A single spiral is typically much smaller than the FoV and can be repeated on a raster pattern to increase the sampling density. Figure 4 shows the path of a single bolometer for a four-point raster of spirals, plotted over the measured footprint on the sky of all the functional bolometers of the array.

The attenuation of the astronomical signals due to the atmospheric opacity is determined with skydips. These scans measure the power of the atmospheric emission as a function of the airmass while tipping the telescope from high to low elevation. Further details on the LABOCA observing modes are accessible at *www.apex-telescope.org/bolometer/laboca.*

During the science verification run in May 2007, the sensitivity on sky (noise equivalent flux density or NEFD) of LABOCA has been determined to be 75 mJy·s$^{1/2}$ (root mean square of weighted average of all 250 functional bolometers). In typical observing conditions of 1 mm of precipitable water vapour (which corresponds to a zenith opacity τ = 0.3), this sensitivity translates into a mapping speed of 1 square degree per hour down

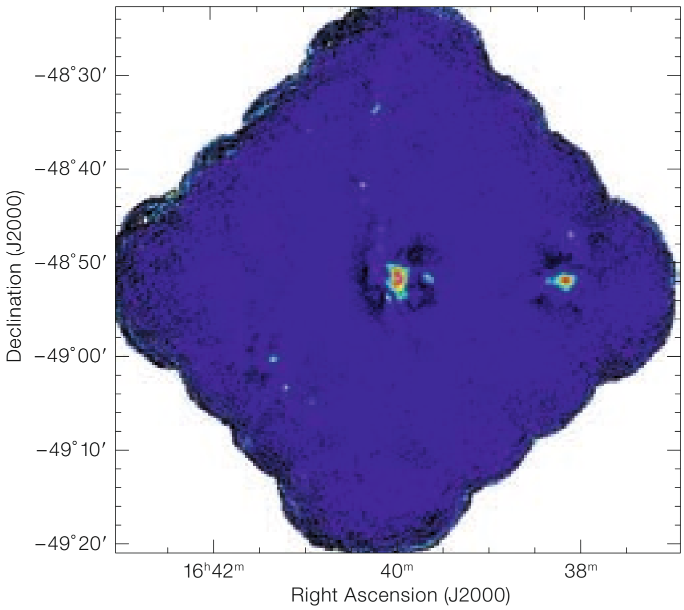

Figure 5: Quarter square degree map observed with LABOCA towards the reflection nebula NGC 6188. The total observing time for this field is only 30 min resulting in a noise level of 35 mJy/beam. The map is a mosaic of raster-spiral patterns.

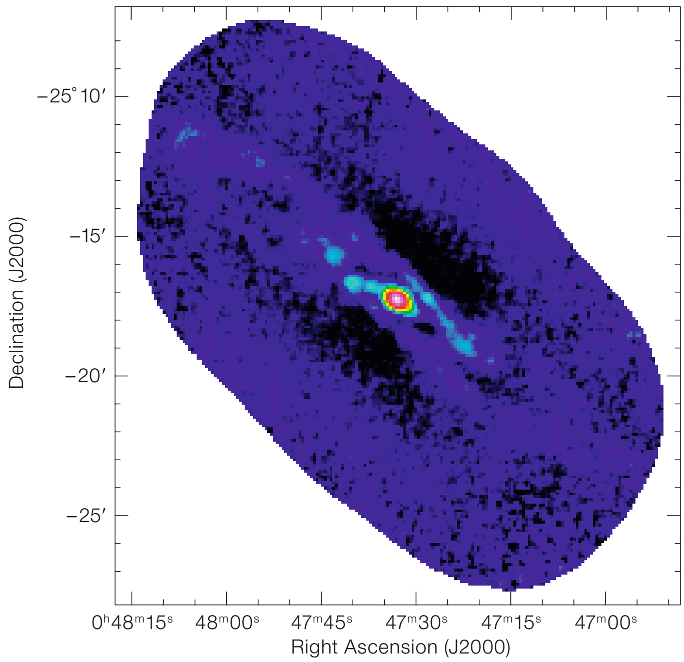

Figure 6: 870 μm emission of the nuclear starburst galaxy NGC 253. The map reveals for the first time the full extension of the low surface-brightness emission arising from the spiral arms in this galaxy.

to a noise level of 40 mJy/beam. An online time estimator for LABOCA is available at *www.apex-telescope.org/bolometer/laboca/obscal.*

Science with LABOCA

On account of its spectral passband, centred at a wavelength of 870 μm, LABOCA is particularly sensitive to thermal emission from cold objects which is of great interest for a number of astrophysical research fields.

Planet formation

The study of Kuiper Belt Objects in the Solar System as well as observations of debris discs of cold dust around nearby main-sequence stars can give vital clues to the formation of our own Solar System and planets in general. With the angular resolution of 18.6 arcseconds, LABOCA will be capable of resolving the debris discs of nearby stars.

Star formation in the Milky Way

The outstanding power of LABOCA in mapping large areas of the sky with high sensitivity (see Figure 5) will allow, for the first time, unbiased surveys of the distribution of the cold dust in the Milky Way to be performed.

As the dust emission at 870 μm is typically optically thin, it is a direct tracer of the gas column density and gas mass. Large-scale surveys in the Milky Way will reveal the distribution and gas properties of a large number of pre-stellar cores in different environments and evolutionary states. Equally importantly, they provide information on the structure of the interstellar medium on large scales at high spatial resolution, an area little explored so far. Such surveys are vital to improve our understanding of the processes that govern star formation as well as the relation between the clump mass spectrum and the stellar initial mass function (IMF).

Large unbiased surveys are also critical for finding precursors of high-mass stars which are undetectable at other wavelengths due to the high obscuration of the massive cores in which they are embedded. LABOCA will help to obtain a detailed understanding of their evolution. In addition, deep surveys of nearby, star-forming clouds, will allow the study of the pre-stellar mass function down to the brown dwarf regime.

Cold gas in Galaxies

The only reliable way to trace the bulk of dust in galaxies is through imaging at submillimetre wavelengths. It is becoming clear that most of the dust mass in spiral galaxies lies in cold, low-surface brightness discs, often extending far from the galactic nucleus (as in the case of the starburst galaxy NGC 253, see Figure 6). Understanding this component is critically important as it dominates the total gas mass in galaxies. For example studies of the Schmidt Law, based on H I observations alone, heavily underestimate the gas surface density in the outer parts of galaxies. In addition to studying individual nearby galaxies, LABOCA will be vital for determining low-*z* benchmarks, such as the local luminosity and dust mass functions, which are required to interpret information from deep cosmological surveys.

Galaxy formation at high redshift

Owing to the advantageous interaction of redshift and the cool dust spectral energy distribution (negative-K correction), submillimetre observations offer equal sensitivity to dusty star forming galaxies over a redshift range from $z \sim 1$–10 and therefore provide information on the star formation history at epochs from about half to only 5 % of the present age of the Universe. Recent studies have shown that the volume density of luminous submillimetre galaxies (SMGs) increases over a thousand-fold out to $z < 2$ (Chapman et al. 2005), and thus, in contrast to the local Universe, luminous obscured galaxies at high redshift could dominate the total bolometric emission from all galaxies at early epochs. These studies also suggest that approximately half of all the stars that have formed by the present day may have formed in highly obscured systems which remain undetected in the optical or NIR. One example of such a source is SMM 14009+0252 (see Figure 7) which is strong in the submillimetre and has a 1.4 GHz radio counterpart, but no obvious counterpart in deep *K*-band images (Ivison et.al. 2000). Clearly it is critical to include these highly-obscured sources in models of galaxy formation in order to obtain a complete understanding of the evolution of galaxies. With its fast mapping capabilities, LABOCA allows us to map fields of half a square degree, typical of the size of deep cosmological fields observed at other wavelengths, down to the confusion limit in a reasonable amount of observing time. These deep observations will also greatly improve the statistics of high-redshift galaxies detected at submillimetre wavelengths.

A set of science verification projects has been observed with LABOCA. The raw and reduced data are publicly available from *http://www.eso.org/sci/activities/apexsv/labocasv/index.html* where more details of the SV programme can be found.

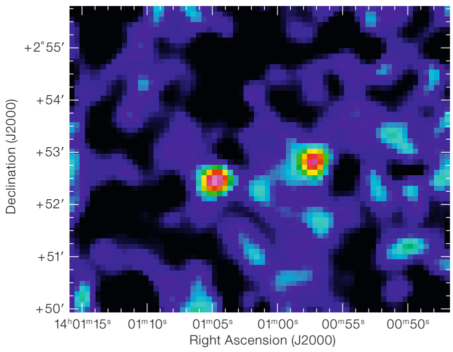

Figure 7: LABOCA image of SMM 14011+0252 (left) and SMM 14009+0252 (right) smoothed to 25 arcsecond resolution. Both submillimetre galaxies were first detected by SCUBA (Ivison et al. 2000). SMM 14011 is at a redshift of $z = 2.56$ (confirmed by CO detections) while SMM 14009 has no clear optical counterpart and therefore no reliable redshift determination. The noise level of the map is about 2.5 mJy/beam.

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Photo: H. H. Heyer, ESO

Left: A view of Comet McNaught, with APEX in the foreground. The photograph was taken on 23 January 2007 when the comet was 10 days past its peak brightness.

Right: APEX/LABOCA 870 micron image of the Horsehead nebula (NGC 2023, also called Barnard 33). The image covers 8.5 by 10.5 arcminutes, and has a spatial resolution of 18.6 arcsec. The inset shows the VLT FORS1 three colour image (from *B*, *V* and *R* filters) of the central 6.5 × 6.7 arcminute (see ESO PR Photo 02a-02 for details). LABOCA traces the emission of the cool dust, which is however seen in absorption in the optical image. LABOCA image produced by the MPIfR LABOCA commissioning team.