The 350 Micrometer Wavelength Superconducting Bolometer Camera for APEX

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Abstract **- Since spring 2008, the Small Array Bolometer Camera (SABOCA) operates at APEX (Atacama Pathfinder Experiment), a 12 meter radio telescope on the high plateau Llano de Chajnantor in Chile's Atacama Desert. This instrument utilizes an array of 37 transition edge sensors to detect sub-millimeter radiation in a narrow band around 350µm wavelength, which fits the last useful atmospheric radio window on earth.**

The TES array is operated at a temperature of 300 mK, enabling a background-limited operation with a measured noise equivalent flux density of around 200 mJy/s$^{1/2}$. SABOCA is the precursor of larger arrays, so it is already equipped with a SQUID time-domain multiplexer, which combines ten bolometer channels each to altogether 4 output channels. We show the configuration of the instrument and present the measured performance under real operating conditions. To our knowledge, this is the first operating superconducting bolometer camera for astronomy entirely conceived and constructed in Europe.

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I. INTRODUCTION

Recent research in astrophysics has yielded amazing new insights in the origins and evolution of our universe. Some of the most interesting information is accessible through observations at sub-millimeter wavelengths. This band contains facts about the early years of the universe, about star formation and planetary accretion.

Most of this progress was achieved due to the availability of extremely sensitive detectors. Amongst them the, so called, transition edge sensor (TES) has emerged as the thus far most effective combination of high sensitivity on one hand and ease of operation on the other.

II. THE BOLOMETER

Basically a TES is a bolometer which transforms the incoming radiation to heat energy by absorbing it in an appropriate antenna. In this way it is possible to measure the temperature raise by means of a sensitive superconducting thermometer. The superconductor is only capable to act as a thermometer in the very narrow region of transition from normal to superconducting state. This implies two consequences: First, one needs a superconducting material with a transition point at the chosen working temperature, and second, this working temperature has to be extremely stable. The idea of the voltage-biased bolometer, as suggested by Irwin *et al*. in 1995 [1] smartly deals with both terms. It utilizes a superconductor whose transition is slightly higher than the bath temperature. In operation it is powered with a constant voltage, V. This bias drives the thermometer to heat up itself to its own transition point. The power of this self-heating P_b is proportional to V^2/R where R is the electrical resistance of the superconducting thermometer at the respective working point. Due to the $1/R$ power dependence, the so called electro-thermal feedback is implemented. As the incident radiation heats up the detector, the increasing resistance of the thermometer intrinsically decreases the self-heating. This effect self-stabilizes the operating temperature. Moreover, it influences the effective thermal coupling, resulting in an effective thermal conductivity G_{eff}.

For the Small Array Bolometer Camera (SABOCA) a TES is used which is operated at a working point around 450 mK. The main challenge in the fabrication is the deposition of the thermistor film, which is a thin-film superconductor with a designed transition temperature T_c. We have chosen sputtered molybdenum (Mo) thin film with a T_c of about 800 mK. By *in situ* sputtering on Mo a thin film of gold and palladium alloy, it is possible to tune the T_c due to the proximity effect [2]. The palladium, which is a strong Pauli paramagnet, causes suppression of T_c much stronger than by a nonmagnetic normal metal. In our case, the T_c can be controllably tuned between 800 mK and 100 mK (see Figure 1). The target T_c can be reproduced from run to run within a 50 mK error margin, and over a period of about one year the measured T_c values have been shown to be stable.

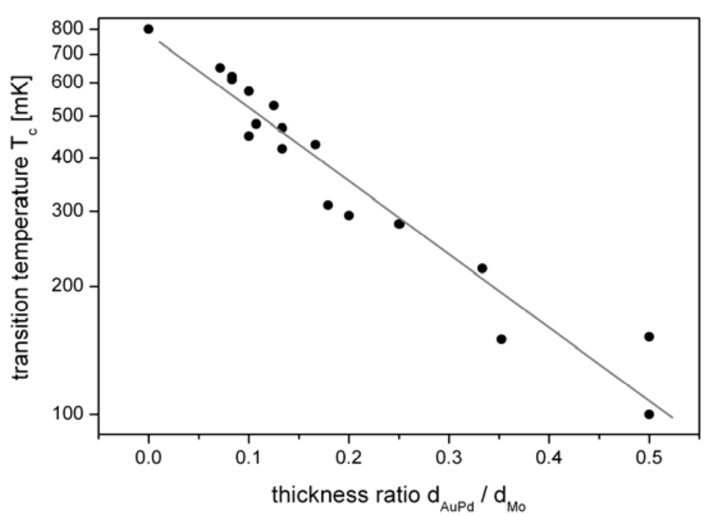

Fig. 1. Dependence of the critical temperature T_C on the thickness ratio of a bilayer of molybdenum and gold-palladium alloy.

The radiation band of interest is coupled to the bolometer via a conical feed horn and a quarter-wavelength back reflector. The energy is absorbed by a small grid of lossy dipole-like antennas whose surface resistances are designed to match the impedance of free space, if one calculates an average resistance over the area of the grid. The absorber dipoles are made of the same gold-palladium alloy that is used in the bilayer film.

Both the thermistor and the absorber are placed on a free-standing silicon nitride membrane to achieve a low thermal conductance and hereby a high sensitivity. Such membranes are manufactured on silicon wafers by removing the silicon underneath a rectangular pattern by an alkali wet etch process. The released SABOCA membrane has a dimension of 800µm x 800µm. Finally, the membrane is patterned using RIE. Ultimately, the membrane thermal conductance is around 1nW/K at 450 mK.

The relatively small TES has a low thermal capacitance, evidenced by a short response time. This is as fast a 50µs, which is interfering with the intended multiplexing readout scheme (see next paragraph). So, an additional gold ring is included in the design, giving an increased thermal capacitance and a time constant of about 1ms.

The detector array for SABOCA consists of 39 TES bolometers, placed on a hexagonal grid with a spacing of 2mm corresponding to the aperture of the conical horn antennas. 2 pixels are redundant to the regular hexagon of 37 pixels. These 2 do not have a horn antenna; the thermal design is, however, exactly the same like for other pixels. In that configuration they will sense, for example, variations in the temperature of the bath. Their output can be used as a reference for the pixels with radiation coupling. Figure 2 shows the SABOCA pixel in the used thermal configuration.

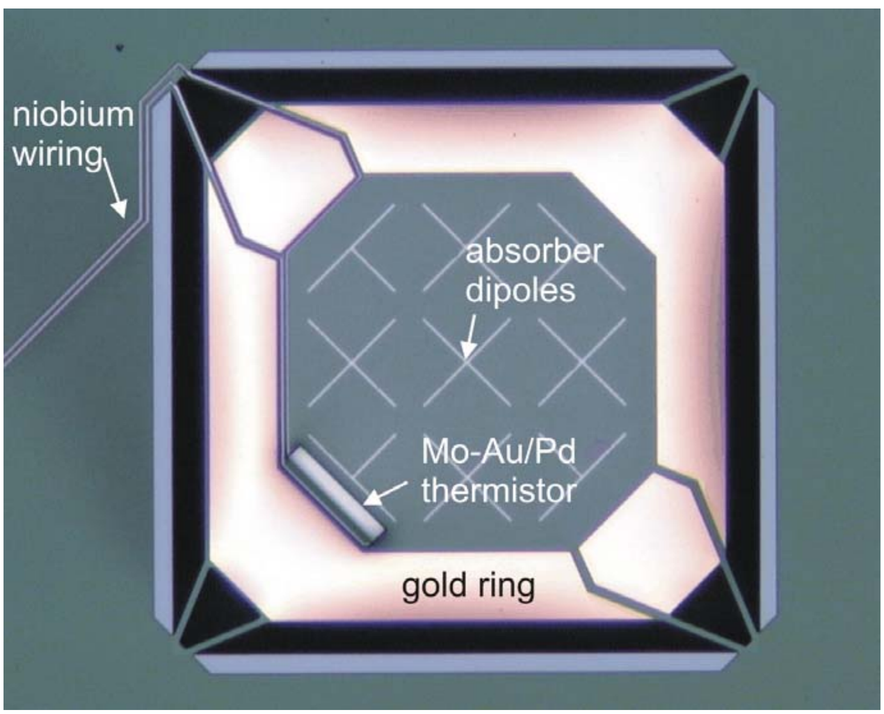

Fig. 2. Micrograph of a single SABOCA pixel.

III. READOUT

With voltage bias, the TES transforms the detected radiation signal into a change of the electrical current flowing through the thermometer. A superconducting quantum interference device (SQUID) in an ampere-meter configuration is used as a low noise amplifier. Despite of the obvious advantage of a SQUID based readout it is one reason for the complexity of TES array sensors. Therefore, recent TES arrays utilize multiplexing schemes to reduce the technical complexity and the cost. The most common approach is the so-called time-domain multiplexing, TDM [3]. The schematic diagram of our TDM circuit is shown in Figure 3.

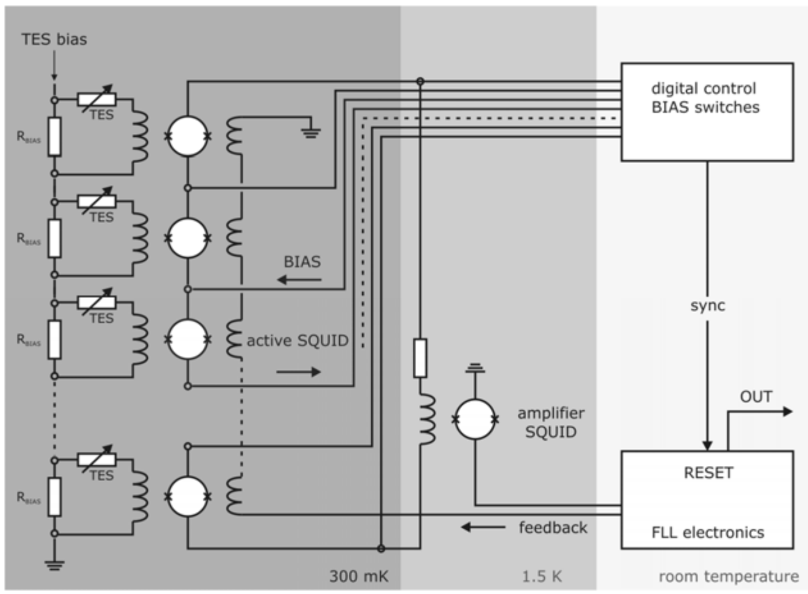

Fig. 3. Time domain multiplexing scheme.

The basic idea of a TDM scheme is to reduce the number of output channels by a serial readout. However, a serial switching of TES is impractical. This is, because the setup of the TES working point requires shortly overheating the bolometer to drive it to its transition. Therefore all TES in an array stay switched on permanently. The TDM is commonly realized by connecting the readout SQUIDs into a superconducting loop. Their common signal is read out by a single second-stage SQUID amplifier; the readout SQUIDs are switched on and off in sequence by means of a digital room-temperature electronic circuit. This can be done much faster than the switching of the TES itself.

The limit of the switching speed is given by the time constant of the electronic loop which controls the SQUID. As the SQUID has a periodical dependence between output (voltage) and input (in this case TES current). Flux-locked loop (FLL) electronics are used to set a stable working point and linearize the output by coupling the measured output amplitude back to the SQUID in a negative feedback scheme. It has to be considered that, in the case of “SQUID with SQUID” read out, the sum characteristic is not sinusoidal as it is typical for a single SQUID. This complicates the loop. For SABOCA, the TDM concept was enhanced by using a superconducting quantum interference filter (SQIF) instead of the SQUID amplifier. Basically, the SQIF is a serial or parallel connection of many SQUIDs with different inductances, designed to generate an unequivocal output signal by superimposing the many different characteristics of single SQUIDs [4]. By using a SQIF, the combined signal of the first stage SQUID and the SQIF amplifier appears as a standard

SQUID characteristic with an amplified voltage swing, which substantially eases the demands on the adjacent electronics*. In the SABOCA implementation, the “SQUID with SQIF” loop can be locked after switching from the antecedent channel within a time frame of around 10µs, allowing for multiplexer switching rates of about 50kHz. However, the potential clock is defined by the data acquisition, as discussed in Section V.

One important thing which has to be considered is that, in the case of time-domain switching, the TES signal of one pixel is quasi-sampled. The sampling rate is the clock divided by the number of channels included in one multiplexer. If the frequency of the modulation of the TES signal is comparable with this sampling rate – or even higher – aliasing effect will increase the noise. For a Nyquist sampling the frequency of this modulation should be at least by a factor of two lower. This implicates the need of high-frequency filtering of the TES signal. Filtering can be accomplished intrinsically by tuning the time constant of the bolometer to an appropriate value, which is done by increasing the thermal capacitance as described in Section II above.

IV. SYSTEM SETUP

The operation temperature is achieved by a ^{3}He sorption cooler with a base temperature of 300 mK and a cooling power of 10µW at 450 mK. The ^{3}He system is self contained; at room temperature a connected bottle stores about 3 liter of ^{3}He gas. Because this gas is liquefied at a temperature below 1.5 K a pre-cooling is needed. There are two options available. SABOCA uses a pumped ^{4}He cryostat with a temperature of about 1.5 K. For the next generation device, the Large Array Bolometer Camera, LABOCA, with 300 pixels we plan to replace the ^{4}He cryostat with a pulse tube cooler (PTC). There are clear reasons for investigating the closed-cycle cooling option. First, providing a continuous supply of liquid helium is costly, second, regular refilling is an enormous task for the site team, and, third, in bad weather conditions it could be impossible to maintain continuity of the camera operation.

The sensor array is encased in a chamber made out of aluminum, which becomes superconducting at 1K and acts as a magnetic shield. The first stage SQUIDs are placed next to the array chip, on 4 chips each integrating 10 ampere-meter SQUIDs in series. The whole chamber is cooled to 300 mK. The thermal load on this stage is dominated by the dissipated energy of the detector bias, whereas the 40 first-stage SQUIDs dissipate on the order of nW and can be neglected. However, even the detector bias load is small enough to potentially enable the implementation of 300 TES for LABOCA, which will increase the thermal load to be around 5µW.

Four rectangular MUX chips are connected to the TES array by aluminum bonds and can be seen in the left photograph of Figure 4 (see next page). Each MUX chip is connected to an amplifier SQIF which is placed on the 1.5 K cooling stage, where the connections are made with superconducting Nb-Ti wires. In addition, 11 Nb-Ti wires are in use for each MUX chip to address the active SQUID corresponding to the TDM scheme in Figure 3.

The filter setup is composed of an IR block at 77K, a cold inductive mesh band-pass filter [5] at 4 Kelvin and the horn antenna with a $\lambda/4$ back short. The results presented in Section V are obtained at a wavelength of 350 µm with a filter band of ±5%.

The complete cryostat with the electronic box containing a digital controller with four

* Details of the SQIF design are proprietary at this time.

FLL electronics and a ring counter for addressing of the MUX SQUIDs can be seen in Figure 5, as it is mounted in the telescope cabin of APEX.

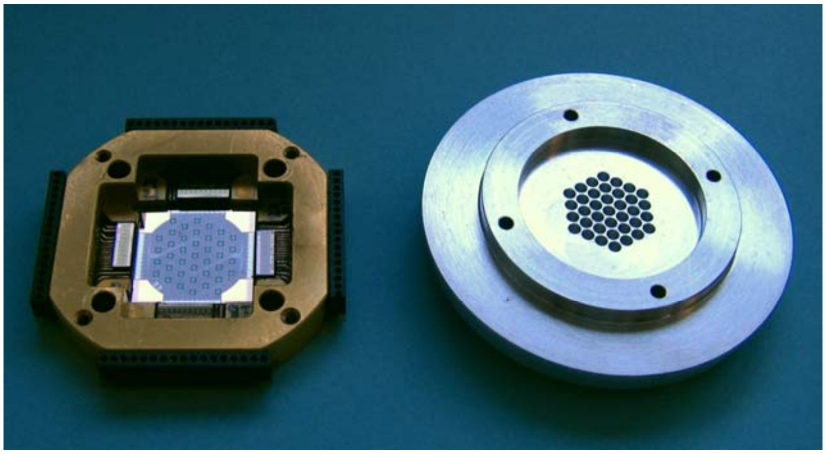

Fig. 4. Array chip integrated with 4 MUX chips in a ring holder (left) and the array of aluminum horn antennas (right)

Fig. 5. The SABOCA cryostat is mounted at APEX telescope cabin.

The device is driven by a data acquisition system, which can be remotely controlled via Ethernet. The data acquisition system is based on a FPGA controlled backplane handling the data from four 24bit A/D converters which digitize the output of the 4 amplifier SQIFs. Although the TDM switching of the first stage SQUIDs can be done with up to 50 kHz, the high-precision digitization allows a switching rate of 2 kHz only, due to its internal anti-aliasing filter.

V. RESULTS

SABOCA has seen first light in spring 2008. During the first installation period it already yielded relevant astronomical science, although the first run was planned as a field test for commissioning by the APEX board. The end of 2008 and beginning of 2009, which corresponds to the summer time at the southern hemisphere and stands for poor observation conditions, was scheduled to put the device into routine operation, which is essential for a facility instrument, which will be operated by personnel not expert in the instrument techniques. During this period, the system parameters have been fully characterized. All of the 40 readout SQUIDs and the adjacent four amplifier SQIFs have been working within the design specifications. One SQUID channel was not connected to a TES and acted as a reference. From the 39 TES one of the redundant pixels was mechanically broken; all other 38 TES are working. Figure 6 shows the typical *I-V* characteristics of 10 TES after demultiplexing. The characteristics show a slight offset, which can be neglected in operation since at a chosen bias voltage all of them exhibit an almost uniform $\delta I/\delta U$ response.

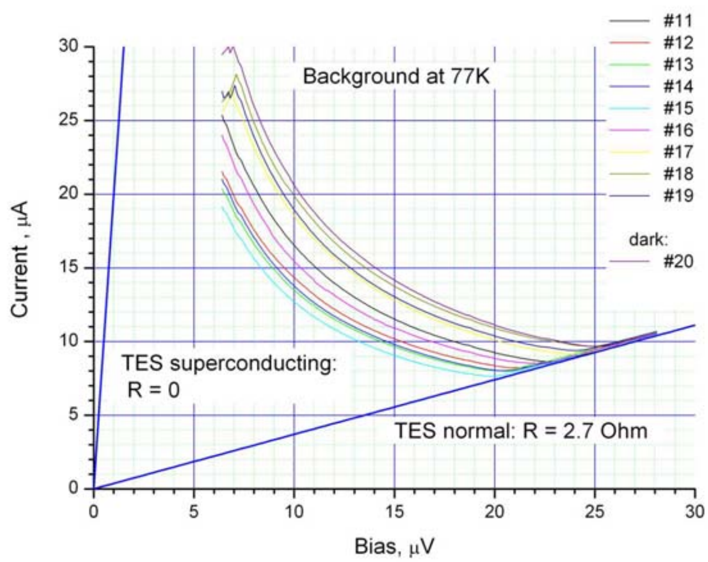

Fig. 6. Current-voltage (I-V) characteristics of 10 TES readout SQUIDs in TDM mode.

The performance of the multiplexing / demultiplexing system was analyzed by keeping the TES inactive. For that purpose, the bias was switched off. In that mode, the TES is superconducting, and the readout senses only the Johnson noise of the bias resistance (R = 50mΩ at 300mK). The Johnson noise to be expected is $2{\cdot}10^{-11}$A/Hz$^{1/2}$. It has to be considered, that a TDM inevitable increases the system noise by a factor of $n^{1/2}$, where n is the number of multiplexed channels. In addition, in the case of the used 24 bit A/D conversion, an additional factor of $2^{1/2}$ is lost because the aliasing filter restricts the bandwidth. So the multiplexer will increase the white noise level by a factor of $20^{1/2}$ ~ 4.5. This is in good agreement with the obtained value, as can be seen in Figure 7. For comparison, the mentioned reference SQUID channel (blue curve, channel 38) shows the intrinsic SQUID noise.

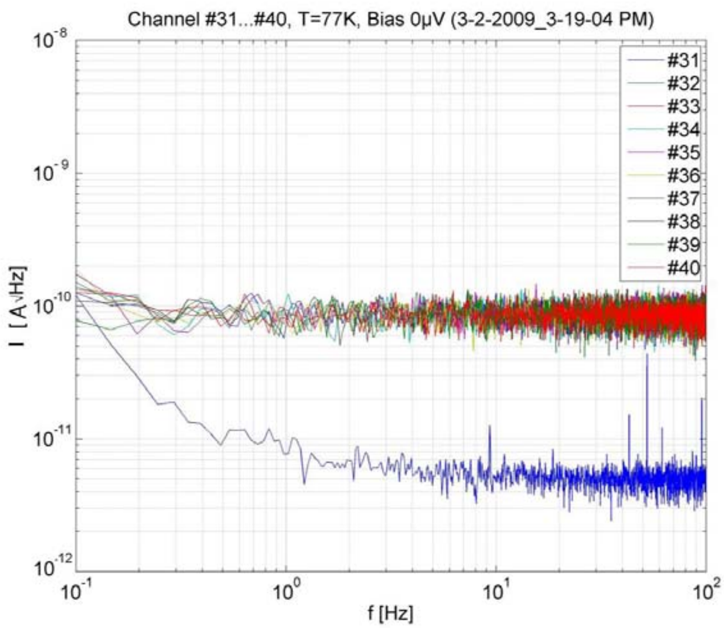

Fig. 7. Johnson noise current signal of 50 mW resistances after multiplexing/demultiplexing: blue curve reference is the intrinsic SQUID noise.

Finally, the optical noise equivalent power (NEP) was measured using a black body cooled to 77K. Figure 8 shows the obtained NEP of $9 \cdot 10^{-16}$W/Hz$^{1/2}$, which is uniform for all pixels. The features noticeable in the spectrum below 7Hz are caused by the boiling liquid nitrogen around the black body.

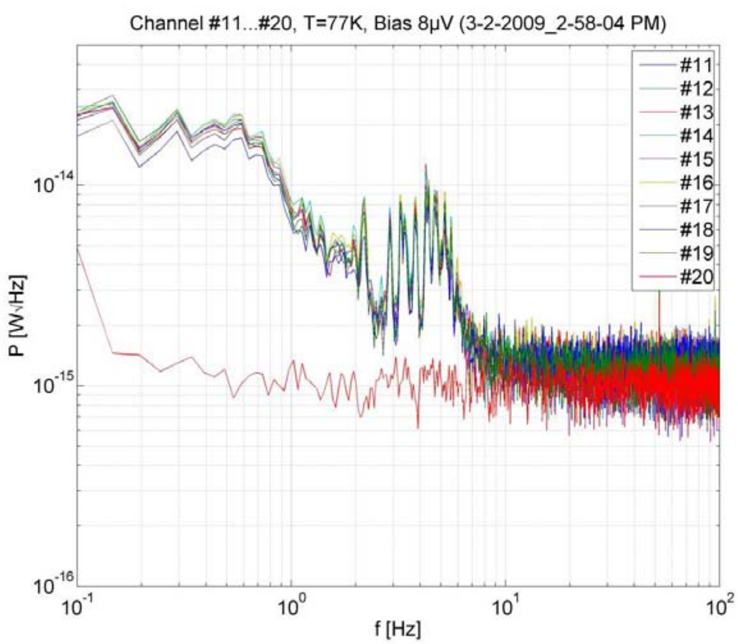

Fig. 8. Optical NEP for 10 TES sensing radiation of a black body at 77K; channel 20 (red curve) is the one redundant pixel without radiation coupling.

The experimentally verified NEP is sufficient to take full advantage of the observation conditions. During observation, water vapor and atmospheric fluctuations usually dominate all other noise sources. Therefore, a comparison between the results from different runs and especially to other instruments is difficult. An instrument at a comparable observation site, the SHARC-II array of Caltech [6] is expected to achieve a noise equivalent flux density NETD of $1 Jy/s^{1/2}$ (1 Jy = 10^{-26} $W/(m^2Hz)$) at good weather conditions. This performance can be exceeded because of the better observation site (APEX is 500m higher). During a run in October 2008, an instrumental sensitivity of 200 $mJy/s^{1/2}$ was achieved and mapping of Orion OMC-1 (see Figure 9) took 1.5 h. The latest run during relatively bad weather still yielded in a NETD of 900 $mJy/s^{1/2}$. In that case the same image would have taken 4 times longer to acquire.

VI. CONCLUSION

The SABOCA camera was successfully installed at APEX and fulfilled the commissioning requirements. It can be handled and remotely controlled by the site team. First astronomical observations, shown in Figure 9, confirmed the expected sensitivity of the instrument and the unprecedented performance of the APEX telescope. SABOCA acts as the precursor for superconducting technologies in astrophysical science: it is the first all-European implementation and anticipates modules which will be used for the next generation instrument: the 300 pixel array LABOCA, scheduled for autumn 2009.

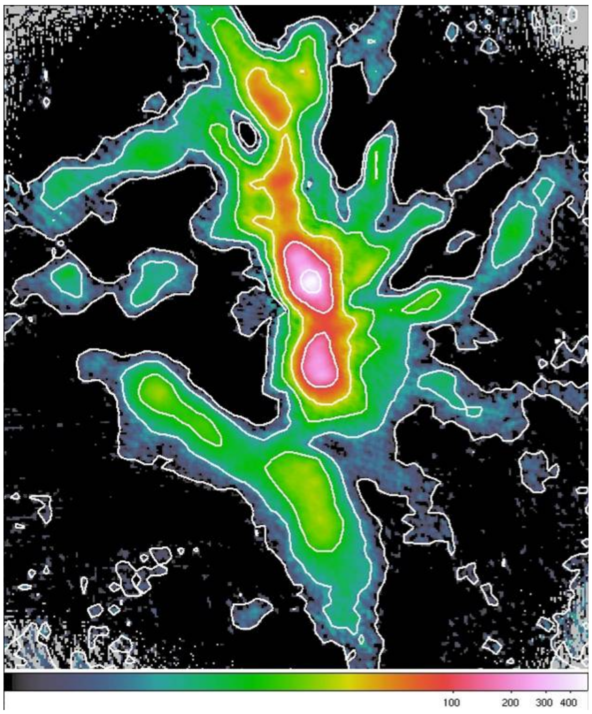

Fig. 9. Orion OMC-1, observed with SABOCA in October 2008. Acquisition time 1.5 hours (contours are 0.5, 3, 10, 30, 100, and 300 Jy levels, 1 Jy = 10^{-26} $W/(m^2 Hz)$)

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