The case for a bolometric millimetre camera at the IRAM 30m telescope

F.–X. Désert [1] & A. Benoit [2]
[1] *Laboratoire d'Astrophysique, Observatoire de Grenoble BP 53, 414 rue de la piscine, F–38041 Grenoble Cedex 9 France*
e-mail: Francois-Xavier.Desert@obs.ujf-grenoble.fr
[2] *CRTBT–CNRS, 25 ave. des Martyrs, BP 166, 38042 Grenoble Cedex 9 France*
e-mail: benoit@polycnrs-gre.fr

Abstract

We describe here the important astrophysical results that could be obtained by using large format (say 32×32) bolometric detectors at 1 and 2 mm with the IRAM 30m telescope: having a confusion–limited 1 mm extragalactic survey containing a large fraction of high redshift objects, mapping star formation regions in our galaxy at 1 mm, and mapping the Sunyaev-Zeldovich effect at 2 mm in tens of high-redshift clusters. We also show a first optical implementation and the key points of this project.

1 Scientific goal

1.1 The 1 mm source counts

Franceschini et al. (1994, see Burigana et al. 1997), Guiderdoni et al. (1998), Blain et al. (1998a, 1998b) have given number counts estimate at the sub–mJy level for a wavelength of 1.3mm, for various galaxy evolution models. It seems that an episode of high rate of star formation is required at high redshift to explain both

- the submillimetre background observed with FIRAS on COBE (Puget et al. 1996, Guiderdoni et al. 1997, Lagache et al. 1998, Fixsen et al. 1998) and with DIRBE on COBE (Hauser et al, 1998)
- and the deep surveys with SCUBA at 850 and 450 μm on the JCMT (Hughes et al. 1998, Eales et al. 1998).

We estimate that one can expect to typically observe 1 galaxy per arcmin^2 above a flux of 1 mJy at 1.2 mm. This corresponds to one source per 30 diffraction beams. So a deep survey with the IRAM 30m should aim at confusion–limited maps with a noise per beam of 0.2 mJy. With an estimated sensitivity of 50 mJy.s$^{1/2}$ (see below), this means that the camera field must be observed for 13 hours, to reach that level. In 100 hours of integration, the number of detected sources with flux above 1 mJy (at the 5σ level) can be expected to be about 70. That would be a major breakthrough in order to study the statistics of this population, even allowing for a factor 2 uncertainty in these numbers. If SCUBA is already finding this population, why should we try to do this in the atmospheric window at 1.2 mm? The answer lies in the now famous positive K–correction that happens for high redshift objects. If SCUBA has a rather strong redshift selection around 3, one can expect a deep 1.2 mm survey to be biased towards redshift 5 objects. Hence, we would probe the evolution of the Universe at large redshifts, for which we know next to nothing. The large collecting area and high angular resolutions of the IRAM 30m telescope would give us a substantial advantage in the search of primeval galaxies. At these wavelengths, the galactic cirrus contamination is much less than in the submillimetre domain, because high redshift objects look colder than the high latitude cirrus clouds.

Millimetre interferometers cannot achieve this mapping speed because their field of view is much smaller. Competition with the future LSA/MMA for surveys has to be carefully studied in this research area.

Surveys at 2.1 mm could be quite important as well; see a first BIMA attempt by Wilner & Wright (1997). The confusion limit would be reached at 0.5 mJy (0.4 galaxies per arcmin^2) in probably less time than at 1.2 mm (5σ in a few hours). But this is very much dependent on the assumptions about the very high redshift Universe (z between 4 and 10).

Blank sky surveys should be done in areas where many complementary data have been accumulated. Obviously the HDF, CFRS and deep radio survey fields are prime targets. Mapping fields around clusters seems also a very powerful technique to observe the high redshift Universe, as done with SCUBA by Smail et al. (1997).

1.2 Mapping star formation regions

The gain in mapping speed will provide much more information on the cold clouds at the origin of the star formation in our galaxy and nearby ones but also it will allow to probe the evolution of the circumstellar material around single and multiple young stars.

This is particularly true for some crucial subjects which are today strongly limited by the sensitivity of current bolometer arrays.

Among them, one can present here a few major topics:

- **Determination of the initial mass function in nearby star-forming region**. Today many of these studies are performed in the main isotopes of CO in J=2-1 or J=1-0 lines because they are easy to detect. In complement to CO studies, deep and large surveys of the optically thin emission of the dust would strongly improve our knowledge of the clump distribution in cloud interiors (Motte et al. 1998).

- **Sensitive mapping at moderate resolution ($\sim 10''$) of the proto-stars (Class 0 and Class I objects)**. These mappings are fundamental because they allow the determination of the total amount of mass surrounding protostars, contrarily to mm interferometers wich resolve out the extended envelope surrounding these objecs (Gueth et al., 1997).
- **Pre-Main-Sequence Stars (Class II objects)** In the more evolve stage of the TTauri phase, most of the envelope has disapeared and the material is in the form of a Keplerian disk (e.g. DM Tau, Guilloteau & Dutrey 1998) which remains unresolved by single-dish telescopes. However, sensitive observations of such objects would help to probe the amount of mass in the outer part of the disk and the extended envelope (if any) where the dust escapes the detection threshold of current mm arrays.
- **Young Stars** Finally, we have now several examples of young stars having dusty disks (similar to the Beta Pic disk). Many new objects have been recently detected and mapped at 0.8mm wavelengths with SCUBA around Solar-type and Vega-type stars (Holland et al., 1998). Sensitive surveys of nearby young stars in the northern hemisphere would help a lot to constrain the amount of dust contained in such debris disks.

1.3 Mapping the CMB anisotropies

At a wavelength of 2.1 mm, it seems that the measurement of the Sunyaev-Zeldovich effect is the least affected by radio sources and dusty galaxies (see the review by Birkinshaw 1998). Mapping the SZ effect with a comptonisation parameter y sensitivity better than 1.5×10^{-5} 1σ per diffraction beam (20 arcsec FWHM) in the core of clusters would be possible in only ten hours. This would be a factor 10-100 increase in mapping speed as compared to SuZie and Diabolo present bolometer experiments. This might be crucial for the follow-up of XMM observations (made with a beam of 15 arcsec) of clusters of galaxies. The other Cosmic Microwave Background (CMB) anisotropies at small scales that are and will be detected by other experiments (the Ryle Telescope and the VLA) could receive an independent confirmation–validation at these clean wavelengths. Sensitivity is the same as above in $\Delta T/T$ units. Millimetre interferometers cannot achieve the sensitivity quoted above for extended sources because of large antennas and the lack of short spacings.

2 Instrument definition

2.1 Requirements

So far, the mapping speed improvements came by adding single elements together. The empirical limit seems to be reached at typically 100 elements. It is limited by the workload (the patience of technicians and engineers: ask SCUBA people for example) of putting things together and by the homogeneity of the array. In general the worst pixels are pulling down the overall sensitivity of the instrument.

Several recent developments in bolometer technology have made integrated arrays possible. Four projects are in various stage of completion: BOLOCAM is an East Coast+Caltech project (Mauskopf & Bock 1998) of 150 integrated 300 mK silicon nitride spider-web pixels with cones separated by one diffraction size to be put at CSO first and then on the future 50m (at 1 and 2 mm). SHARC (and further) is an operational camera (made by Moseley et al. at NASA–GSFC) of a 24 pixel single line that can be stacked to others in the future, and that works at a temperature of 300 mK and a wavelength of 450 μm at the CSO (Wang et al. 1996). In France, the CEA–LETI–Grenoble (P. Agnese) is developping a 32×32 square array as the baseline for the SPIRE bolometer instrument onboard FIRST (200 to 500 μm). It uses the Silicon chip making process to make a fully integrated array. Another development is with the NbSi thin layers by the IN2P3–CSNSM–Orsay (L. Dumoulin).

So if these technologies are available in Europe, what could be the best use of them in the millimetre domain? In what configuration? We argue here that to make full use of the multiplex advantage, the cone at each pixel must be dropped (as is now planned for SPIRE). A cone optimises the f/D ratio and hence minimises the pixel size. In case of lenses, the pixel scale at the focal plane is necessarily larger. A cone also clearly defines the entrance acceptance angle, effectively defining the pupil and reducing sidelobes. So, why dropping the cones? First, the new bolometer technology allows larger pixels without loss in sensitivity (heat capacity is reduced by making thinner bolometers). Then, by using a cold pupil common to all pixels, one can still prevent most of the sidelobes and heatload on the detector.

Moreover, additional problems arise from cones that can be solved by using an appropriate filled array. The most efficient (straight instead of parabolic) cones, as in the best known examples (37 bolometer MPIfR and SCUBA), are packed at a spacing of only twice the diffraction size on the sky, thus mapping at a time, a fraction of 1/4 of the available sky. The sky map must be filled with a drizzle technics using 16 different positions to have a fair sampling. This is a likely source of noise, because the map is not fully acquired at the same time. Another matter of concern is the anomalous refraction which is known to happen at Pico Veleta and at the JCMT. Even a strong source has an apparent jitter in front of a detector, giving a so-called source noise. Calibrations and photometrical measurements are thus more difficult. When reaching the confusion limit, anomalous refraction may be a strong limitation. Therefore, it seems that a cleaner and more efficient solution is to have a filled array of pixels covering the largest available sky but also at the same time, fairly sampling the whole available sky (say at half the diffraction per pixel) in front of a cold pupil. This is the current basic design of most infrared cameras. The SHARC experiment is already designed this way.

So far the available arrays are modulated with a wobbling secondary. A total power readout technique could alleviate the use of a wobbler. This is already in use by small bolometer arrays: SuZie, NOBA, and Diabolo at POM2. In the case of a large array, the most promising observing technique is to fix the telescope in local coordinates ahead of the target and let the sky drift with the diurnal motion. Local effects and flat field can thus be disantangled from the real sources.

Table 1: Sensitivity evaluation

Characteristics	units	**1**	**2**
Wavelength	mm	1.2	2.1
Heat load	pW/pix	23	2.5
Photon noise	10^{-17} WHz$^{-0.5}$	17	5
Assumed Pix. noise	10^{-17} WHz$^{-0.5}$	10	5
Point Source 1σ, 1s.	mJy	50	25

2.2 A preliminary implementation

Figure 1 shows a possible optical layout of the bolometric camera at 1.2 mm. It uses one warm lens (assumed here in polyethylene with a n=1.47 index of refraction) at the 30m focal plane and one cold lens at the pupil image of the secondary. This cold pupil lens closes the 1.6K box. Note that the pixel size is here 2.6 mm (i.e. larger than the operating wavelength) and that is samples half a diffraction size. Filters (not shown) have to be placed at the cold pupil or just in front of it at 4 K or higher. The camera at 2.1 mm may require bigger pixels, hence may be 16 by 16 pixel wide. The field of view would typically be of 3 by 3 arcminutes, i.e 256 independent beams at 1.2 mm.

Table 1 gives the expected sensitivity as conservative estimates. For that, we assume a very mediocre state of the atmosphere and the telescope: atmospheric opacity (at the measurement elevation) and temperature of resp. 0.4 at 1.2 mm and 250 K, telescope emissivity and main beam efficiency of resp. 0.1 and 0.25 at 1.2 mm and 0.50 at 2.1 mm. The filtering is assumed to have an overall transmission of 15 percent in a $\delta\lambda/\lambda \simeq 0.30$ bandwidth. The box enclosing the detector must be kept at 1.6K to avoid overloading the detectors. Most of the photon noise is due to the atmosphere, and not to the telescope. The same calculation adapted to the present 37-bolometer array and Diabolo experiments give sensitivities which are slightly above what has been obtained on the sky. The needed detector sensitivity can be achieved with the present technology, on single bolometers, especially with relatively slow time constant. This sensitivity of arrays should be coming soon. Cooling the detector to 0.1 K might be advantageous in this respect.

2.3 A list of potential problems

We list here several open issues that should be dealt with before designing such an instrument.

- Which array of detectors can we foresee to use?
- Should we use lenses or ellipsoid mirrors as in SHARC?
- Filtering: use a dichroic to have simultaneously the 1 & 2mm channels (as in Diabolo) or use a filter wheel or make two separate cryostats on a similar design to match the detector

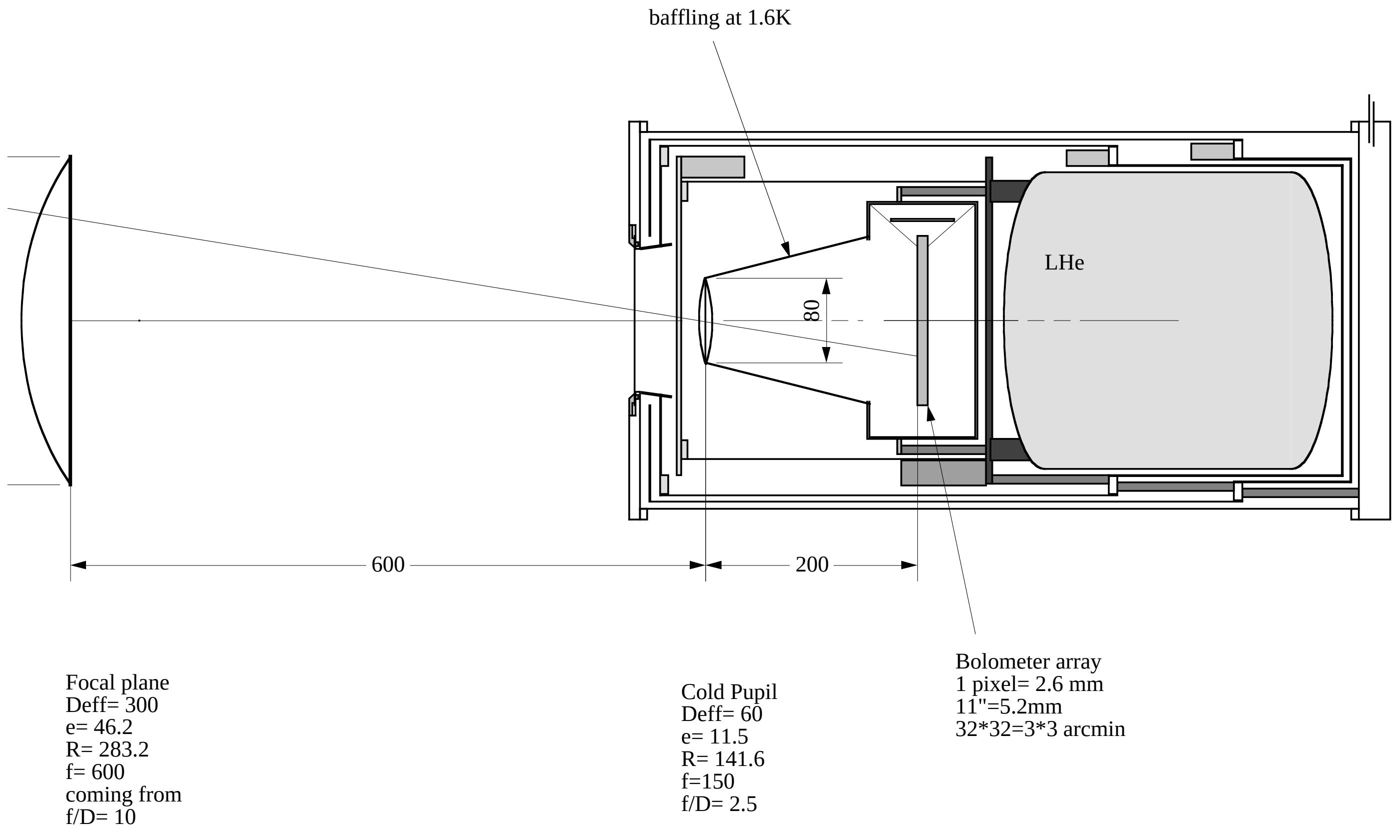

Figure 1: A schematic optical layout

to the wavelength?

- The readout technique is not yet settled and depends on the used array. Multiplexing bolometers has not yet been reported.
- Cooling to 0.3 K or 0.1 K, with cryocoolers or a cryostat?
- Stray light should be a major concern at the start. Ray-tracing and Gaussian optics should be used to predict and deal with the biggest sources of stray light and ghost images. Warm baffling may be used to avoid modulated stray light.

3 Conclusions

Having a truly mapping millimetre instrument would bring the same qualitative changes as we saw 15 years ago when IR cameras arrived at the telescope and replaced single element detectors. The modern submillimetre instruments are near or at the confusion limit in extragalactic and galactic environments. Data acquired with arrays having cones may be very hard to exploit. A true camera has a potentially large multiplex gain and cleaner behaviour at the confusion limit. The IRAM 30m user community clearly has to discuss the various options before attempting to build such an instrument. We think the challenge is really worth the efforts and that the time is ripe to start a definition study. We here suggest to continue pre–design studies and then build the instrument which could be soon fitted with prototypical detectors of 5 by 5 or 8 by 8 but which would also be compatible with future 32 by 32 bolometer arrays.

Acknowledgements. We thank P. Agnese, L. Dumoulin, A. Dutrey, S. Guilloteau, J.-M. Lamarre and B. Lazareff for many helpful discussions.

References

[1] Blain, A. W., Ivison, R. J., & Smail, I., 1998, astro-ph/9710003 v2

[2] Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.–P. 1998, astro-ph/9806062

[3] Birkinshaw, M., Physics Reports, submitted, astro-ph/9808050

[4] Burigana, C., Danese, L., De Zotti, G. et al., 1997, MNRAS, 287, L17

[5] Eales, S. A., Lilly, S. J., Gear, W. K., et al., 1998, ApJL, submitted (astro-ph/9808040)

[6] Fixsen, D. J., Dwek, E., Mather, J. C., et al., 1998, ApJ, in press (astro-ph/9803021)

[7] Franceschini, A., Mazzei, P., De Zotti, G., Danese, L., 1994, ApJ, 427, 140

[8] Gueth et al., 1997, A&A 323, 943

[9] Guilloteau, S. & Dutrey, A. 1998, A&A 339, 467

[10] Guiderdoni, B., Bouchet, F. R., Puget, J.–L., et al., 1998, Nature, in press, astro-ph/9706095

[11] Guiderdoni, B., Hivon, E., Bouchet, F. R., & Maffei, B., 1998, MNRAS, 295, 877

[12] Hauser, M. G., 1998, ApJ, in press (astro-ph/9806167)

[13] Holland et al., 1998 Nature 392, 788

[14] Hughes, D. H., Serjeant, S., Dunlop, J. et al., Nature, 394, 241

[15] Lagache, G., et al, 1998, A&A, in press

[16] Mauskopf, P., & Bock, J., 1998, `http://www-lmt.phast.umass.edu/ins/continuum/bolocam.html`

[17] Motte, F. et al. 1998, A&A , 336, 150

[18] Puget, J.–L., Abergel, A., Bernard, J.–P., et al. 1996, A&A, 308, L5

[19] Smail, I., Ivison, R. J., & Blain, A. W., 1997, ApJ, 490, L5

[20] Wang N., Hunter, T. R., Benford, D. J. et al., 1996, Applied Optics, 35, 6629

[21] Wilner, D. J., & Wright, M. C. H., 1997, ApJL, 488, L67