Hence the predicted versus observed $Y$-parameter are for the 2-mm channel:

$$(Y)_{X-ray} = -2.73\ 10^{-4}\, h_{50}^{-1/2}$$
$$(Y)_{obs} = -2.53\ 10^{-4} \qquad (7)$$

giving a formal result of the Hubble constant of $H_0 = 58^{+35}_{-22}$ km $s^{-1}$ $Mpc^{-1}$.

As the reader is aware, the error bars are quite large. They take into account many uncertainties still involved in this kind of measurements: the pointing position of the SEST and ROSAT Telescopes, the X-ray modelling and the uncertainties of the mm observations. These latter consider also the fact that the 1.2-mm channel is very likely affected by secondary cluster emission, maybe due to intracluster dust and/or sources.

The only way to get rid of these systematics is the observation of many clusters. Every source in fact contributes in a different way to the various modelling steps so that it is reasonable to assume that the average value of the Hubble constant is a fair estimate of the real one.

This project would never have become a reality without the work of many people, among them I would like to thank my collaborators (H. Böhringer, R. Booth, G. Dall'Oglio, R. Lemke, L. Martinis, L.-Å. Nyman, A. Otàrola, L. Pizzo, P. Shaver, N. Whyborn), the SEST team and the Infrared group at La Silla and in particular Glenn Persson, Roland Lemke, Angel Otàrola, Peter de Bruin, Cathy Horellou, Peter Sinclair and Nicolas Haddad for their fundamental help and assistance during the observations and during the photometer set-up. This work has been partially supported by the P.N.R.A. (Programma Nazionale di Ricerche in Antartide). P.A. warmly thanks ESO for their hospitality during 1995, when part of this work was carried out.

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# Cold Dust in Galaxies

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## Abstract

The activity of galaxies reaches from the enhanced star-formation rate to the outburst of quasars. These different aspects of converting cold gas into luminosity can be well described by the ratio of infrared luminosity versus gas mass. The process of star formation is characterised by $L_{IR}/M_{gas}$ values of 5 [$L_\odot/M_\odot$] in normal spirals and 100 in active Mkn galaxies while quasars attain values above 500 due to additional non-thermal processes. Moreover, the coldest dust component in extragalactic objects also seems to be correlated with the stage of activity: $T_d$ increases from 15 K in normal spirals to more than 40 K in quasars. New *ISOPHOT* data between 60 and 200 μm and SEST data at 1300 μm corroborate these results for active galaxies but indicate the presence of very cold dust ≈ 10 K) in normal spirals. The implications on the total gas content of galaxies are discussed. It turns out that high-resolution submm measurements of the dust emission with high spatial and spectral resolution play a key role for our understanding of the interstellar medium in external galaxies. In this context, plans for SIMBA, a new 37-channel bolometer array at 1300 μm for the SEST and the need for the LSA are briefly discussed.

## 1. Activity in Galaxies

In a previous *Messenger* article (Chini and Krügel, 1996, hereafter Paper I) we have described our long-term project on the global star- formation efficiency in various classes of galaxies. Our approach to this problem was the following: The energy of most galaxies originates from the formation of stars; only a few exotic objects like radio galaxies and quasars contain additional sources of energy which probably originate from the accretion of interstellar matter onto a circumnuclear disk. However, both sources of energy have in common that cold interstellar gas is transformed into luminosity. Therefore, the amount of luminosity obtained per unit gas mass, i.e. the ratio $L/M_{gas}$, should be an appropriate description for the activity in galaxies.

In order to obtain this ratio, we determined the two fundamental quantities $L$ and $M_{gas}$ for three samples of normal spirals, active galaxies and radio-quiet quasars. The total luminosity was approximated by the IR luminosity between 12 and 1300 μm. This interval is nicely covered by the infrared satellite *IRAS* at the wavebands 12, 25, 60 and 100 μm; beyond that we managed to obtain the 1300-μm continuum flux from the 15-m SEST or the 30-m IRAM telescope. The luminosity $L_{IR}$ derived in this way is typically a factor of 10 higher than the blue luminosity $L_B$, indicating that it is a good approximation for the total luminosity of these objects.

The gas content $M_{gas}$ of the galaxies was determined from the optically thin emission of dust at 1300 μm observed at the SEST and at IRAM. To convert the observed dust emission into a gas mass we used the fact that in the Milky Way, the amount of gas is about 150 times larger than that of dust. An independent check of the gas mass was derived from CO measurements: the intensity of the lower rotational levels J(1-0) and J(2-1) at wavelengths of 2.6 mm and 1.3 mm, respectively, has been verified empirically to be proportional to the mass of molecular hydrogen. The corresponding observations have also been performed at the SEST and the IRAM 30-m telescope. The major results of these studies as outlined in Paper I can be summarised as follows:

1. In normal spirals the spectral energy distribution from 100 to 1300 μm is dominated by cold dust of $T_d = 15 \pm 5$ K. Their gas mass is $2 \cdot 10^9 \leq M_{gas} \leq 6 \cdot 10^{10}$ $M_\odot$ and their IR luminosity is $6 \cdot 10^9 \leq L_{IR} \leq 3 \cdot 10^{11}$ $L_\odot$ yielding a ratio $L_{IR}/M_{gas} = 5 \pm 2$ in solar units.

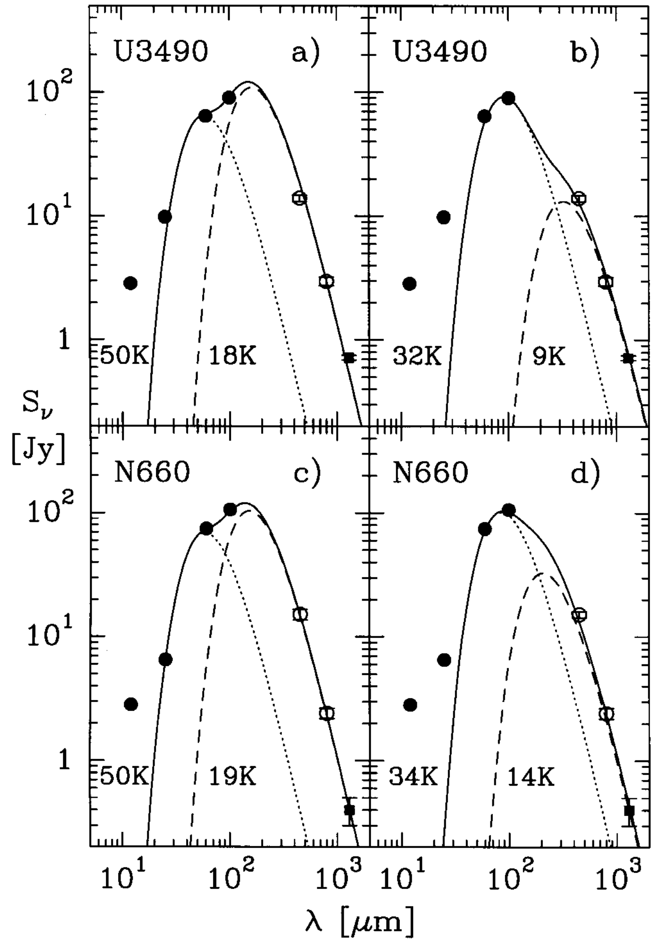


*Figure 1: Observed energy distributions of UGC 3490 and NGC 660. Measurements at 450 and 800 μm are from Chini & Krügel (1993) and 1300 μm data come from Chini et al. (1995). Possible decompositions into a cold (dashed) and a warm (dotted) component are shown assuming* m *= 2. The temperatures of the individual components are (a) 18 K and 50 K, (b) 9 K and 32 K, (c) 19 K and 50 K, (d) 14 K and 34 K.*

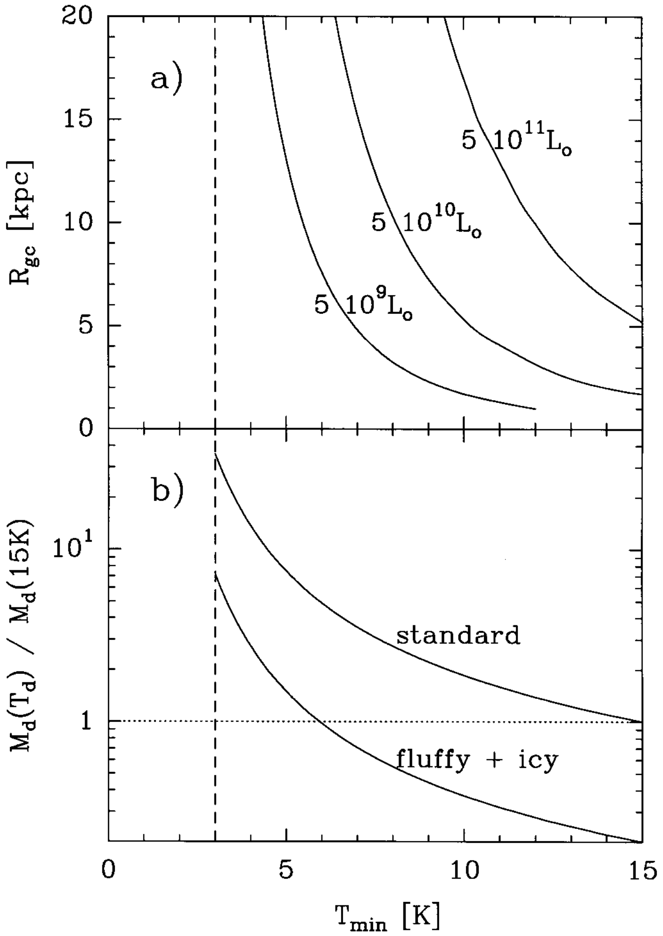


*Figure 2: (a) Minimum dust temperature $T_{min}$ as a function of galactocentric radius $R_{gc}$ for $L_{IR} = 5 \cdot 10^9$, $5 \cdot 10^{10}$ and $5 \cdot 10^{11}$ $L_\odot$, respectively. (b) The relative change of dust mass compared to a 15 K component for normal (solid) and fluffy + icy grains (dashed) where $\kappa_{1300}$ is enhanced by a factor of 5.*

2. In active galaxies the spectral energy distribution from 60 to 1300 μm can be described by a coldest dust component of 33 ± 5 K. We find a range of gas masses of $5 \cdot 10^7 \leq M_{gas} \leq 8 \cdot 10^{10}$ $M_\odot$ and a range of IR luminosities of to $5 \cdot 10^9 \leq L_{IR} \leq 3 \cdot 10^{12}$ $L_\odot$. The ratio $L_{IR}/M_{gas} = 92 \pm 53$, i.e. about a factor of 20 higher than in normal spirals.

3. In radio-quiet quasars, finally, the coldest dust component was found to be about 40K. Their gas content is comparable to that in active galaxies but their ratio $L_{IR}/M_{gas} \approx 550$.

Thus, there is a correlation between the stage of activity and the $L_{IR}/M_{gas}$ ratio as shown in Figure 2 of Paper I. Obviously, the luminosity is no unique indicator for activity because extragalactic objects within the luminosity interval from $10^{11}$ to $10^{12}$ occur as normal spirals, active galaxies or quasars. Likewise, objects of a given gas mass produce quite different amounts of luminosity, depending on their activity. Thus only the efficiency of converting mass into luminosity, i.e. the quantity $L_{IR}/M_{gas}$ determines the actual stage of activity. Non-active galaxies are characterised by rather low ratios of the order of 5 whereas active galaxies produce 20 times more luminosity out of the same reservoir of gas. Obviously, the range $5 \leq L_{IR}/M_{gas} \leq 100$ is typical for star formation, whereas larger values, as they occur with quasars, require additional non-thermal processes. In this paper we want to address the importance of the dust temperature and its implication for the activity in galaxies.

## 2. The Dust Content of Galaxies

The stage of activity as measured by the ratio $L_{IR}/M_{gas}$ seems also to be correlated with the temperature of the coldest dust component in galaxies. According to our previous measurements, dust in normal galaxies attains temperatures as low as 15 K and increases to about 40 K in quasars. As discussed above, the origin of this effect cannot entirely be attributed to the amount of luminosity (because there are normal and active galaxies with identical luminosity), but rather must be dominated by some geometrical effects. Vice versa, the temperature of the coldest dust component determines the total amount of dust and gas and thus scales with the ratio $L_{IR}/M_{gas}$ directly. In this sense, $T_d$ becomes an extremely important quantity which, however, is difficult to determine accurately because of the large gap in the data between 100 and 1300 μm.

### *2.1 The decomposition of spectral energy distributions*

To overcome the problem of insufficient spectral coverage and to improve the temperature estimates we have started to fill the gap between 100 and 1300 μm by submm continuum measurements from the JCMT at 450 and 800 μm (Chini *et al.* 1995). Figure 1 shows as an example the spectral energy distribution (SED) of two galaxies, UGC 3490 and NGC 660, where we have included some of the missing spectral points. In order to derive the temperature $T_d$ of the coldest dust component we applied fits of the form $\lambda^{-2} B_\lambda(T_d)$ where $B_\lambda$ denotes the Planck function and the factor $\lambda^{-2}$ accounts for the emissivity of the dust grains. Interestingly, despite the additional submm data, the SEDs still cannot be interpreted in a unique way: The emission from UGC 3490 within the range 60 to 1300 μm may be described by two components of 9 K and 32 K (case *a*) but also by a superposition of two temperatures at 18 K and 50 K (case *b*). For NGC 660 the differences are not that extreme but possible solutions still vary between combinations of 19 K and 50 K (case *c*) or 14 K and 34 K (case *d*). This means that even additional submm data at 450 and 800 μm are not sufficient to clarify the problem of spectral decomposition. On the contrary, the new data rise the important question whether a very cold dust component exists in galaxies.

## 2.2 Is there very cold dust in galaxies?

In Paper I we derived an average temperature for the coldest dust component of 15 ± 5 K in normal spirals and 33 ± 3 K in active Mkn galaxies. It is clear that a whole range of warmer dust is required to explain the entire emission at wavelengths shorter than 60 μm; the amount of material at higher temperatures, however, is negligible in the context of the total mass of interstellar matter in galaxies. On the other hand, observational uncertainties and ambiguities in decomposing the SEDs, leave sufficient freedom for the existence of still colder dust in substantial quantities. The importance of the temperature of the coldest dust component in galaxies is twofold:

1. The optically thin emission of dust at submm wavelengths $S_\lambda$ is directly proportional to the amount of dust $M_d$ and depends on the temperature $T_d$:

$$M_d = \frac{S_\lambda}{B_\lambda(T_d)} \frac{D^2}{\kappa_\lambda}, \qquad (1)$$

where $B_\lambda$ denotes the Planck function, $\kappa_\lambda$ the mass absorption coefficient and $D$ the distance. Using the Rayleigh-Jeans approximation $B_\lambda(T_d) = 2hc^2/\lambda^2 \bullet k\, T_d$ the dust mass becomes inversely proportional to the dust temperature ($T_d$)

$$M_d = \frac{S_\lambda}{T_d} \frac{\lambda^2}{2hc^2 k} \frac{D^2}{\kappa_\lambda}. \qquad (2)$$

If the 1300 μm flux observed at SEST originates from very cold dust, the total amount of interstellar matter increases and thus our numerical results concerning the activity tracer $L_{IR}/M_{gas}$ have to be revised.

2. Because the emitted energy is proportional $T^6_d$, a slight decrease in dust temperature causes a large change in the energy balance of a galaxy. It may imply that (i) the average stellar luminosity per unit volume is lower or (ii) the dust is farther away from the stars or (iii) the dust is better shielded from stellar photons.

In order to estimate the minimum possible temperature $T_{min}$ of dust, we neglect both, the possible interstellar matter outside the optical radius of a galaxy and the existence of very small transiently heated particles, which are most of the time at very low temperatures, but do not contribute significantly to the total dust mass.

Very cold dust can only be found deep in the interior of clouds; it must be protected from stellar light and shielded by an optical depth well above 10 mag. Nevertheless, at least for wavelengths beyond 25 μm, clouds are heated by the FIR emission of the galaxy itself. There the optical depth is probably more than a factor of 50 smaller than in the visual. The heating by FIR radiation is not very efficient because of reduced cross sections for absorption, but it is much more important than the heating by the microwave background. To further minimise the heating, we assume that the source of FIR radiation resides in the galactic nucleus. A spatially spread-out energy source, like stars in the disk or heating by radiation of shorter wavelengths, would only increase $T_{min}$.

The results for $T_{min}$ are shown in Figure 2a, which is reproduced from Chini & Krügel (1996). The calculations are based on two heating components of equal luminosity with a $\lambda^{-2}B_\lambda(T_d)$ spectral shape and temperatures of 15 K and 50 K. Obviously, in a galaxy with an FIR luminosity of $5 \cdot 10^{10}$ $L_\odot$ and an optical size of 15 kpc, like e.g. the Milky Way, the dust in the disk cannot become colder than ~ 6 K; two additional curves in Figure 2 show how $T_{min}$ depends on the luminosity of the galaxy.

To estimate how much dust mass can escape detection, we make the extreme assumption that the observed 1300 μm flux originates entirely from very cold dust without any contribution from a 15 K component. From the solid curve in Figure 2b, which holds for normal dust in the diffuse interstellar medium, we can infer by how much we would underrate the mass of dust at a certain temperature assuming that $T_d$ were 15 K; for example, dust of 6 K would yield a factor of 5. The optical properties of very cold dust, however, are inevitably modified by the deposit of ice mantles and, most likely, coagulation into fluffy agglomerates. This modification leads to an increase in the absorption coefficient κ by a factor of 5 to 10. Consequently, the mass of very cold dust may even be slightly smaller or comparable to the dust at 15 K (see Figure 2b dashed curve); dust of 6 K, e.g., would leave the mass unchanged. As the two effects, lower temperature and enhanced grain emissivity, neutralise each other we conclude that 1300 μm continuum observations yield fair results for the total dust mass.

## 2.3 Latest answers from ISO

Recently we have combined new *ISOPHOT* data between 60 and 200 μm with 1300 μm observations for six galaxies (Krügel et al., 1998). Eight ISOPHOT wavebands have been selected to cover the peak of the dust emission and thus to derive a very accurate determination of the dust temperature $T_d$. Three of the objects come from our sample of active Mkn galaxies (see Fig. 3, reproduced from Krügel et al., 1998). Their SEDs can be fitted uniquely by a single dust component of 31 K which is in perfect agreement with our previous estimates.

For the three normal spirals the picture changes considerably: As shown in Figure 4 (adapted from Krügel et al., 1998), least square fits to the data from 60 to 1300 μm require a combination of two dust components – one of about 29 K which dominates the *ISOPHOT* observations and another one of about 10 K which is necessary to explain the 1300 μm emission observed at SEST. Depending on the mass absorption coefficient κ this very cold component may imply an increase of the mass of interstellar matter by a factor of three. As a consequence, the ratio $L_{IR}/M_{gas}$ could be reduced by the

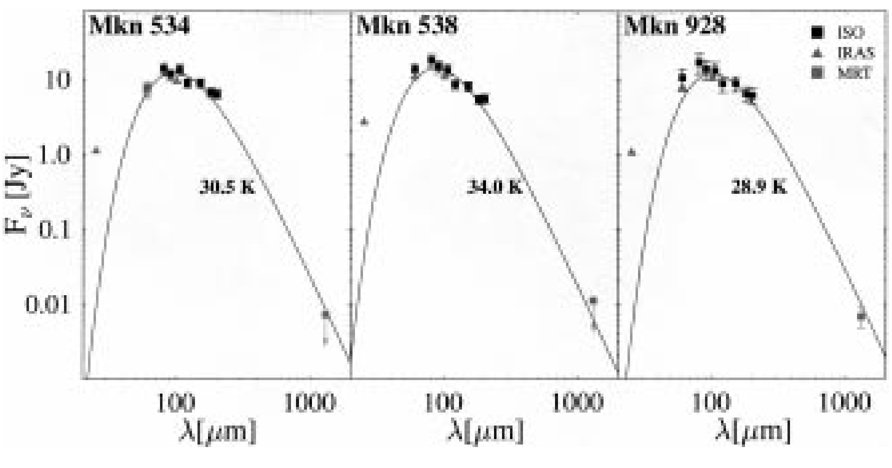


*Figure 3: Dust emission spectra of three active galaxies from the Markarian catalogue. The solid lines are one-component fits between 60 and 1300 μm of the form* $\lambda^{-2}B_\lambda(T_d)$; *the resulting fit temperatures are indicated.*

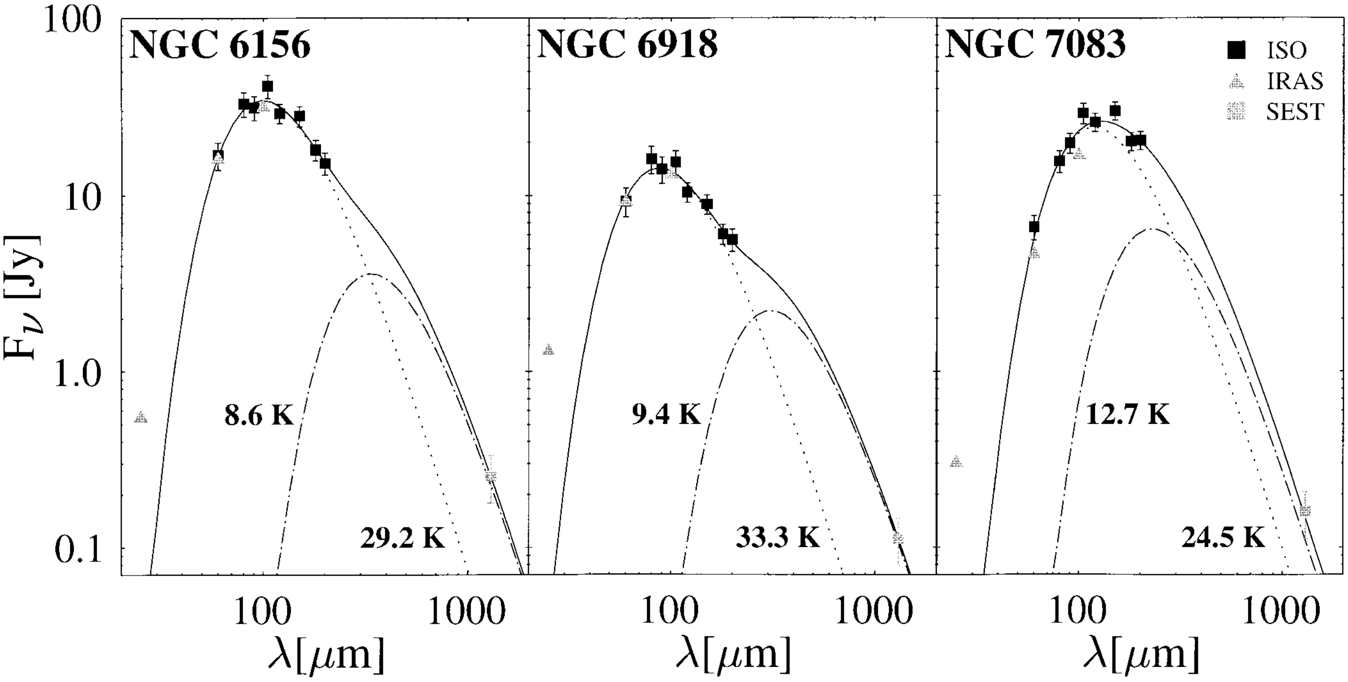


*Figure 4: Dust emission spectra of three inactive spiral galaxies. The dotted and dashed-dotted lines are two-component least square fits between 60 and 1300 μm of the form $\lambda^{-2}B_{\lambda}(T_d)$; the solid curves give their sum. The resulting fit temperatures are indicated.*

same amount. Certainly, the number of galaxies is still Insufficient to draw general conclusions, but evidence grows that large amounts of cold dust may be present in normal spiral galaxies.

## 3. Future Developments

Despite the interesting results obtained so far there is obviously heavy demand for an improvement in the decomposition of the SEDs by data of better spectral and spatial resolution and for a complete coverage of extended objects at several submm wavelengths. In order to meet some of these requirements, there are two instrumental developments in the southern hemisphere that will hopefully enrich the observational possibilities in the future:

**SIMBA**. Measurements of the total dust emission from extended sources like galactic molecular clouds or external galaxies require time consuming mapping procedures: The present 1300 μm continuum detector at SEST consists of a single bolometer element that provides a field of view of only 24 arcseconds. Due to the generally faint extended millimetre emission, continuous mapping is restricted to the brightest objects. Fainter sources have to be observed with ON-OFF procedures that take at least 5 hours to perform e.g. a crude 5-point raster map. As a result, the spatial distribution of dust is so far unknown and/or incomplete for most galaxies and has to be extrapolated. Therefore, the "Astronomisches Institut der Ruhr-Universität Bochum" and the "Max-Planck-Institut für Radioastronomie" in Bonn have agreed upon designing a new $^3$He-cooled 37-channel bolometer array as a facility device for SEST (SIMBA = SEST IMaging Bolometer Array) with support from Onsala Space Observatory. The new system will operate at a wavelength of 1300 μm and at a spatial resolution of 24 arcsec. With a total field of view of about 300 arcsec in diameter, SIMBA will allow to cover large regions like southern molecular clouds and galaxies and in particular the Magellanic Clouds with unprecedented sensitivity and efficiency. Apart from a factor of 37 in integration time such a multi-channel system has a number of further advantages compared to the existing single channel device: Performing e.g. 37 individual maps of an area implies huge overheads due to repeated pointing and calibration actions between the single coverages whereas a 37-channel map can be run with one pointing and calibration only. Another gain comes when coadding the 37 channels: Individual coverages from a single-channel observation suffer from unavoidable positional uncertainties and thus smear out faint extended structures in the final superimposed image. In contrast, the final map from the new array detector will always produce "sharp" images because the offset between the 37 individual channels is mechanically fixed and well known. Even point-source measurements will benefit from the new device tremendously when using the outer channels of the array to monitor sky fluctuations. Depending on the weather conditions, improvements of factors 2–3 in sky-noise suppression have been achieved with a similar system at the IRAM 30-m telescope. SIMBA will be manufactured throughout 1998 and it is planned to install the system in April 1999 after the new wobbling secondary for SEST has been implemented.

**LSA**. Apart from measuring the total flux of an object, one is also interested in the detailed spatial distribution of the emission. There is strong evidence, that e.g. most of the interstellar gas in active galaxies is concentrated within an inner region of a few kpc – possibly in form of disks, rings or bars. Likewise, the configuration of interstellar matter in the host galaxies of quasars is entirely unknown, due to insufficient spatial resolution. In order to disentangle fine structures in the mass distribution, spatial resolution of the order of one arcsec or better is required. This can only be managed by future submm interferometers such as the LSA. Located at an appropriate high altitude site, this instrument will eventually be able to fill up the spectral gap between 200 and 1300 μm as set by current air- and spaceborne missions and ground-based observations from SEST and IRAM. Only the simultaneous increase of spatial and spectral resolution will improve our understanding of the origin of global star formation, starbursts and quasars.

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