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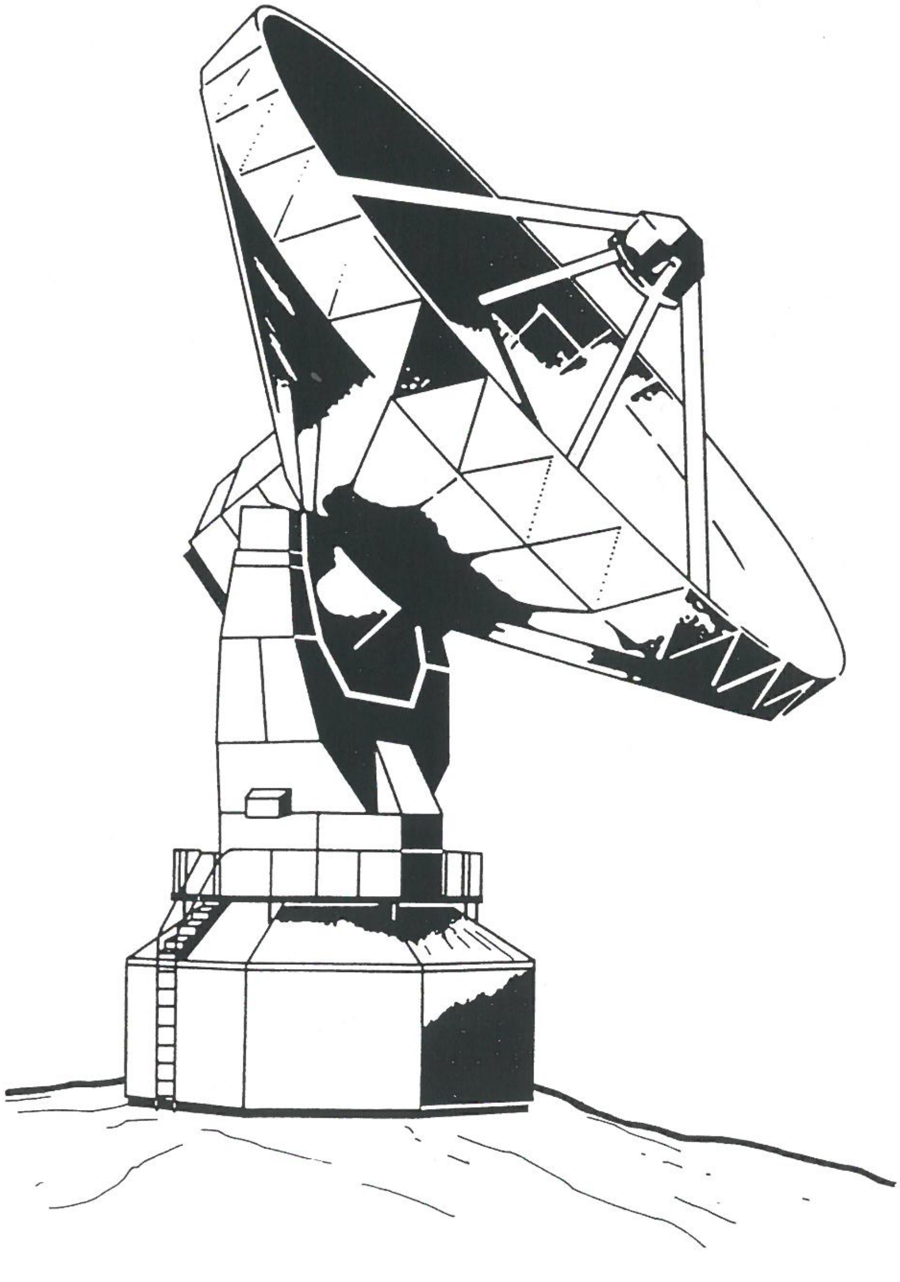
DANS L'HEMISPHERE AUSTRAL

(Sub)Millimeter Astronomy at ESO



(Sub)Millimeter Astronomy at ESO

A Report

for the Meeting of the STC

on 5-6 May 1994

ESO Garching

11 April 1994

Summary

The SEST is unique as the only large (sub)millimeter telescope in the southern hemisphere. It has been in regular operation since 1988, providing opportunities to the ESO community for spectroscopic observations at 0.8, 1.3, and 3 mm and continuum (bolometer) observations at 1.3 mm. The agreement between Sweden and ESO runs to 1999, with discussion of possible prolongation to take place in 1997. This report summarizes the place of the SEST in the field of (sub)millimeter astronomy, both scientifically and technically, and makes several proposals for further development.

The SEST facility has been very cost-effective. The annual cost to ESO (including salaries and all support) is about 1.3 mDM, *i.e.* about 2.6% of ESO's annual budget excluding the VLT and VLT-related salaries; or, considering just expenditures in Chile, the SEST costs are about 3.5% of the La Silla budget. The SEST is also inexpensive compared to other similar facilities around the world: its total annual operations and development costs are only about one-quarter, and its staff about one-third, of that elsewhere.

In spite of this very modest investment, the SEST has been efficient and productive, as summarized in this report. The demand for observing time is the same as at other similar facilities, and on a par with the large ESO optical telescopes when the difference in observing efficiency is taken into account. However, the financial and manpower constraints have meant that there has been only a limited capacity to deal decisively with new or persistent technical problems, or to maintain a high level of investment in state-of-the-art receivers. Furthermore, in view of the much larger investments being made at similar facilities elsewhere (especially on receiver arrays), some increased investment will be necessary if the SEST is to remain at the forefront of (sub)millimeter astronomy.

The (sub)millimeter band is one of the frontier areas of astronomy, so the potential scientific returns from an investment are high. The next major step is to arrays of telescopes, and several nations have already expressed interest in the idea of a large mm array in the southern hemisphere, possibly Paranal. An expression of support by ESO for such an array would help such efforts.

This report makes the following proposals for further development:

(1) The SEST should continue to be supported, at least at the present level and at least for the duration of the present agreement with Sweden.

(2) A number of modest upgrades should be made to the present facilities (Table 11a), and some minor revisions (*cf.* Section 5.3) should be made to the SEST budgetary arrangements within ESO.

(3) The staffing situation should be reviewed, taking into account desired upgrades and improvements and the move to a Santiago base, and specific proposals made for appropriate increases, if warranted.

(4) A feasibility study of a nutating subreflector and other possible alternatives to facilitate observations with receiver arrays on the SEST should be undertaken as a matter of priority.

(5) The feasibility, cost, and potential advantages of a possible move of the SEST to the Paranal area should be explored in some detail.

(6) The results of (4) and (5) should be considered at the next STC meeting, together with specific proposals for future developments.

(7) ESO should express its support for the possible eventual development and operation of a (sub)millimeter array in the Paranal area.

(8) Finally, a standing working group on (sub)millimeter astronomy should be established to study these and other relevant matters, and to make recommendations to ESO.

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1. Introduction

Ten years have now elapsed since the agreement was signed between Sweden and ESO regarding the SEST - already two-thirds of the way into the 15-year term of the agreement - and the SEST iteslf has been in regular operation for six years. For this reason, and also in the context of the "streamlining" of La Silla, it was thought timely to review the productivity and technical state of the SEST, and begin to elaborate new plans for the future, including upgrades, new instrumentation, and a possible move to Paranal.

This report was commissioned last month to provide background for a review of the SEST which will take place at the forthcoming meeting of the STC on 5-6 May. It will also serve as the basis for a one-day meeting of a working group comprised of specialists in (sub)millimeter astronomy, convened specifically for this purpose. This working group will meet on 19 April, and present its recommendations to the STC.

The report summarizes some of the work that has been done at the SEST, and places it in the context of (sub)millimeter astronomy generally. Comparisons are made with other (sub)millimeter facilities around the world. The technical state of the SEST facility is reviewed, and suggestions made for improvements and upgrades. Finally, in view of the considerable interest which has been shown in several countries, ideas for the possible development of a (sub)millimeter array at Paranal are summarized.

This report was prepared with the help of several persons, in particular Roy Booth at Onsala, Lars-Ake Nyman at La Silla, those whose names appear with the 19 scientific summaries in Section 2, and others who very kindly provided up-to-date information about other (sub)millimeter facilities around the world.

P. Shaver

11 April 1994

2. Millimeter and Submillimeter Astronomy

2.1 (Sub)Millimeter Astronomy and the SEST

In several respects the (sub)millimeter band is one of the richest in astronomy. It contains the peak of the microwave background radiation (fig. 1) and the whole panoply of molecular line astronomy (*e.g.* fig. 2). It lies at the cross-roads of many different kinds of astronomy, containing the synchrotron and free-free emission which dominate the radio centimeter bands, the thermal emission of the optical and infrared bands, and the cool dust emission which peaks in the (sub)millimeter band itself.

Observations which have been made at (sub)millimeter wavelengths touch virtually all areas of astronomy. The isotropy of the microwave background has been studied over a range of angular scales, with important implications for the physics of the early Universe and the formation of large-scale structure, and measurements have been made of the Sunyaev-Zeldovich effect which hold out the promise of determining H_o. A recent and very important development has been the detection of CO and dust emission from some of the most distant known objects (redshifts in the range 2.3-4.7), suggesting that observations at (sub)millimeter wavelengths may be the best (or even the only) way of detecting primeval galaxies at still higher redshifts. Observations in the (sub)millimeter band have been important additions to simultaneous broadband monitoring of active galactic nuclei, crucial for the understanding of the broadband spectra and nature of radio-quiet and radio-loud quasars and other types of AGN.

Millimeter-wavelength Very Long Baseline Interferometry is still in its infancy, but of course it holds great promise, both because of the higher resolution possible for a given baseline (an eath-diameter baseline at 1 mm provides 20 μarcsecond resolution) and also because the AGN studied are less opaque due to synchrotron self-absorption at these higher frequencies, enabling one to explore much smaller scales closer to the active nucleus. Millimeter interferometry gives the highest resolution images ever obtained in astronomy.

Studies involving continuum observations and molecular line spectroscopy have been made on a large number of different types of galaxies. The bolometer (continuum) observations probe the dust content of galaxies, as well as the nonthermal nuclear emission. Spectroscopic observations explore molecular gas in a wide range of physical conditions, with spectral resolutions unattainable at optical wavelengths and in regions which are often optically obscured. Early-type galaxies, spirals of all types, interacting and ring galaxies, starburst galaxies, and galaxies in groups and clusters have all been extensively studied. Centaurus A and the Magellanic Clouds have provided unique opportunities in the southern hemisphere.

In our own Galaxy, molecular line surveys of the galactic plane have provided new insights into the large-scale distribution of gas and star-forming regions. The dependence of isotopic ratios on galactocentric distance has been an important input to theories of stellar and chemical evolution over the galactic plane. Modern astrochemistry started only two decades ago with the radio detections of molecules in dense galactic clouds. Today

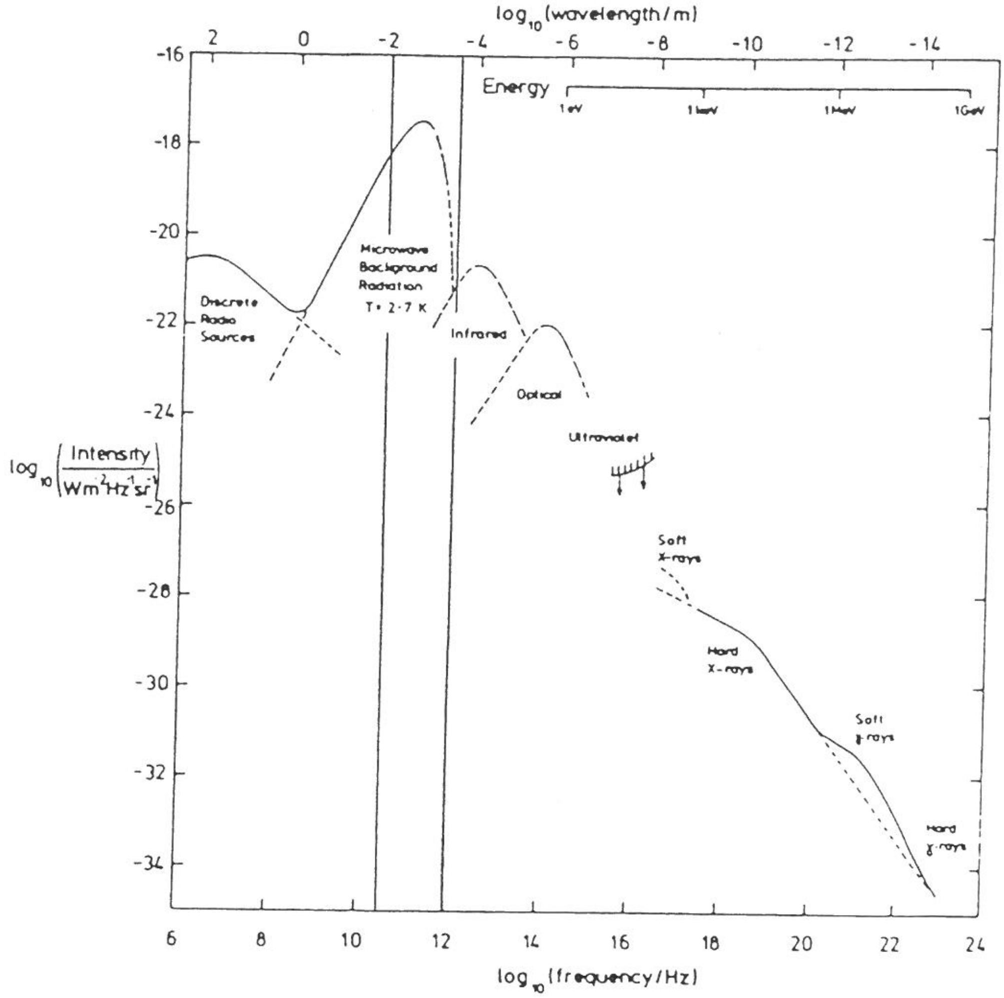


Figure 1

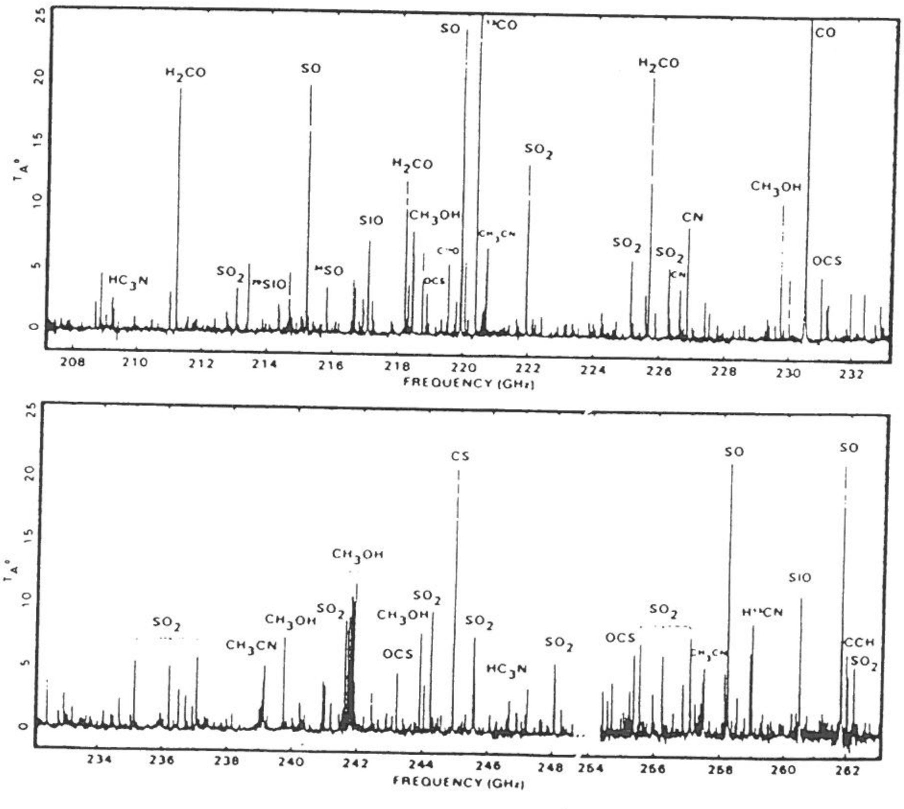


Figure 2

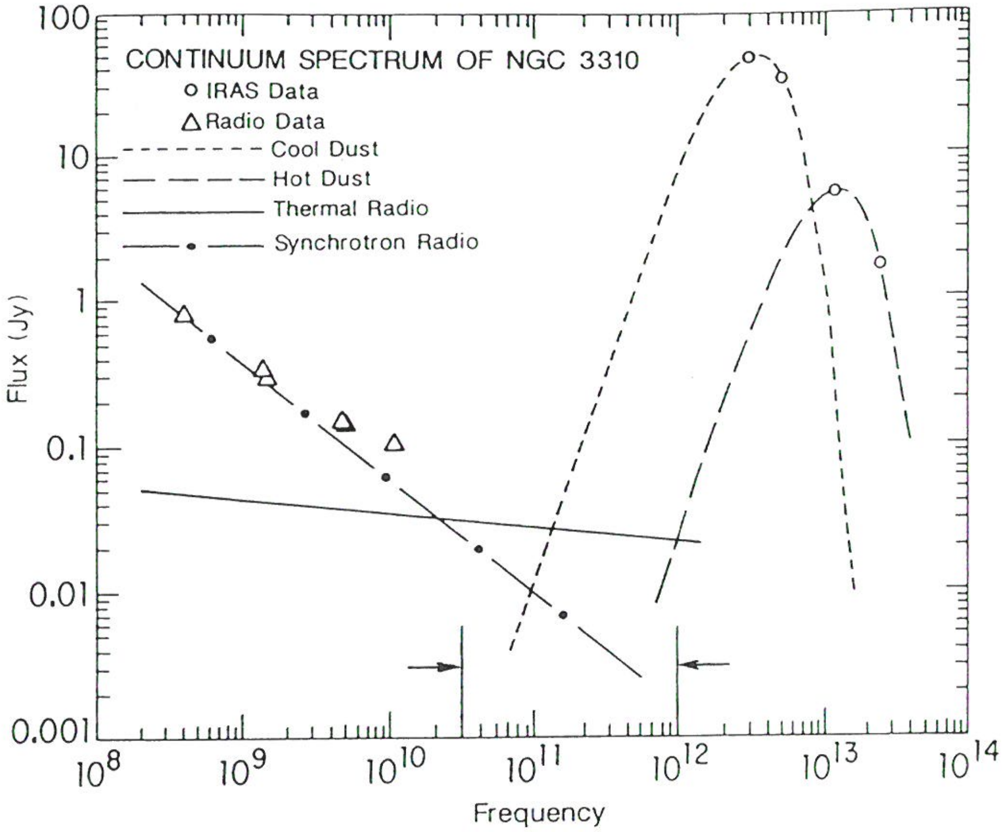


Figure 3

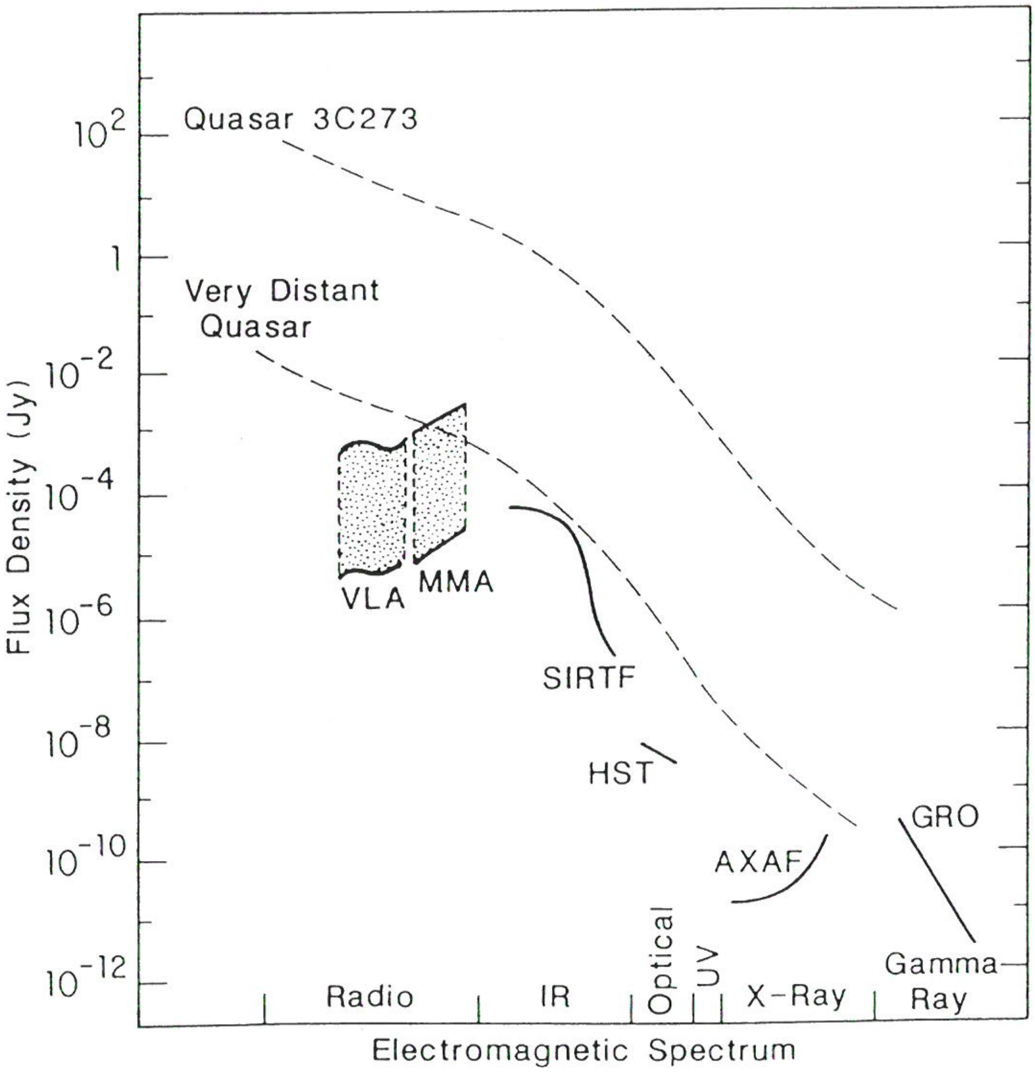


Figure 4

there are over ninety interstellar and circumstellar molecular species known, including molecules with as many as thirteen atoms and some non-terrestrial species (the spectrum of the Orion Molecular Cloud shown in fig. 2 contains more than one thousand lines identified with about thirty different molecular species - millimeter spectroscopy of cosmic molecules rivals in richness the Fraunhofer spectrum of the sun). The different molecules and transitions probe different physical conditions and opacities, providing great diagnostic power. The study of chemical abundances in molecular clouds gives evidence for the survival of interstellar molecular material in primitive solar system objects, and allows the study of conditions relevant, perhaps, to the origin of life itself.

Understanding the processes of star formation, one of the key problem areas for all astronomy, has been a major goal of (sub)millimeter astronomy. Molecular spectroscopy first revealed the fast outflows characteristic of very young stars, and now bolometer continuum searches are being made for true protostars - cold objects which are still collapsing and have not yet generated the energy to show up even as infrared objects. This is a search which can *only* be made in the (sub)millimeter band.

The circumstellar envelopes of stars in late evolutionary stages have provided a rich field for study in the (sub)millimeter. These often host SiO masers, and molecular line and (dust) continuum observations give important new information on mass loss rates and the structure and chemistry of these envelopes. Optical and infrared studies are often hampered by obscuration; the (sub)millimeter emission arises from the cool gas further from the star, and so gives a better estimate of the shell mass than infrared data.

(Sub)millimeter studies of disks around main-sequence stars provide information about dust grain size, and so constrain models of the formation of planetary systems. (Sub)-millimeter studies have also contributed to various aspects of solar system research, from the nuclei of comets and the very weak emission from their cool tails, to the chemical composition of planetary atmospheres and the physics of the sun.

In its six-year life the SEST has already made many important contributions to most of the areas mentioned above, as summarized in Table 1 and the (partial) list of publications in Appendix 1. One of the great advantages of a user-friendly facility like the SEST being included amongst the ESO telescopes at La Silla is that it has attracted optical astronomers to extend their work to the (sub)millimeter domain and make "broad-spectrum" studies of specific astrophysical problems. Some of the work done using the SEST in a variety of areas is summarized below.

Cosmology and The High-Redshift Universe

The microwave background is best studied in the (sub)millimeter waveband, as it peaks in the middle of this waveband (fig. 1), and contaminating effects from galactic thermal and nonthermal radiation on the one hand and dust emission on the other are at a minimum (fig. 3). The best work is, of course, done from satellites, above the earth's atmosphere (*e.g.*, COBE). Nevertheless, useful contributions are also being made from ground-based facilities, including the SEST. During searches for millimeter continuum emission from

Table 1. Science with SEST

Cosmology

- CN Measurements for CBR Temperature Determination
- Sunyaev-Zeldovich Effect in Clusters of Galaxies

High-Redshift Universe

- CO Emission from high-z Galaxies and QSOs
- CII 158μm Emission from High-z Galaxies and QSOs
- Dust Emission from High-z Galaxies and QSOs
- CO Absorption in QSO spectra

Active Galactic Nuclei

- Millimeter VLBI Observations of AGN
- Simultaneous Broad-Band Spectra of AGN
- Dust Emission from Compact Steep-Spectrum Sources
- Seyfert Galaxies
- Millimeter Emission from Optical Jets
- Molecular Emission and Absorption in Centaurus A Nucleus and Dust Lane

Nearby Galaxies and Clusters

- IRAS and Starburst Galaxies
- OH Megamaser Galaxies
- NGC 253, NGC 1808, NGC 4945 Studies
- Interacting, Merging, and Ring Galaxies
- Wolf-Rayet Galaxies
- Irregular Galaxies
- Markarian Galaxies
- Barred Spirals
- Normal Spirals
- Molecular Gas in Early-type Galaxies
- Dwarf Galaxies
- Millimeter Continuum Emission from Galaxies
- CO Emission in Compact Groups of Galaxies
- CO Emission from Galaxies in Clusters
- CO Emission/Absorption in Cooling flows

Magellanic Clouds

- Magellanic Clouds Key Programme
- Millimeter Continuum Emission from SN 1987A

Molecular Clouds

- Interstellar Chemistry
- Isotopic Ratios, versus Galactocentric Distance
- Molecular Clouds at Large Galactocentric Radii
- Giant Molecular Clouds, Dark Clouds
- Cometary/Bok Globules
- Reflection Nebulae
- Diffuse Clouds, IRAS Cirrus
- Translucent Clouds
- Molecular Clouds adjacent to Supernova Remnants (Puppis A, RCW 103, etc.)
- Galactic Centre Molecular Clouds (High-Velocity Flows, etc.)

Star Formation Regions

- Compact HII Regions
- IRAS Sources, Maser Sources
- Outflows from Young Stars
- T-Tauri Stars
- Herbig-Haro Objects
- Radio Recombination Lines from eta Carina
- Millimeter Continuum Emission from Cold Protostars

Stars and Late Stellar Evolutionary Stages

- Circumstellar/Protoplanetary Disks
- Wolf-Rayet Stars
- RV Tauri Variable Stars
- Be Stars
- Binary systems
- S Stars
- Carbon Stars
- Symbiotic Stars
- Mira Variables
- AGB and Post-AGB Stars
- Novae
- Planetary Nebulae

Solar System

- CO Emission Emission and Absorption from Mars
- Millimeter Continuum Emission from Asteriods

radio-quiet quasars using the bolometer on the SEST, Chini *et al.* and Andreani *et al.* (see below) found that their non-detections could be used to place useful limits on the isotropy of the microwave background. The SEST played a useful role in what were, until COBE, the most accurate determinations of the microwave background temperature (Crane *et al.*, 1989, Ap.J. 346, 136). These employed optical interstellar CN observations towards galactic stars, and the SEST contribution was to set limits on the possible contribution from local excitation mechanisms by searching for CN emission at 2.64 mm. Finally, the Sunyaev-Zeldovich effect, which conserves photons and produces a shift in the CBR blackbody spectrum towards higher frequencies, can in principle be observed as a decrement longward of the peak and an excess shortward of the peak. Observations straddling the peak are therefore best placed to detect an unambiguous signal. The first attempts using the SEST will take place this year.

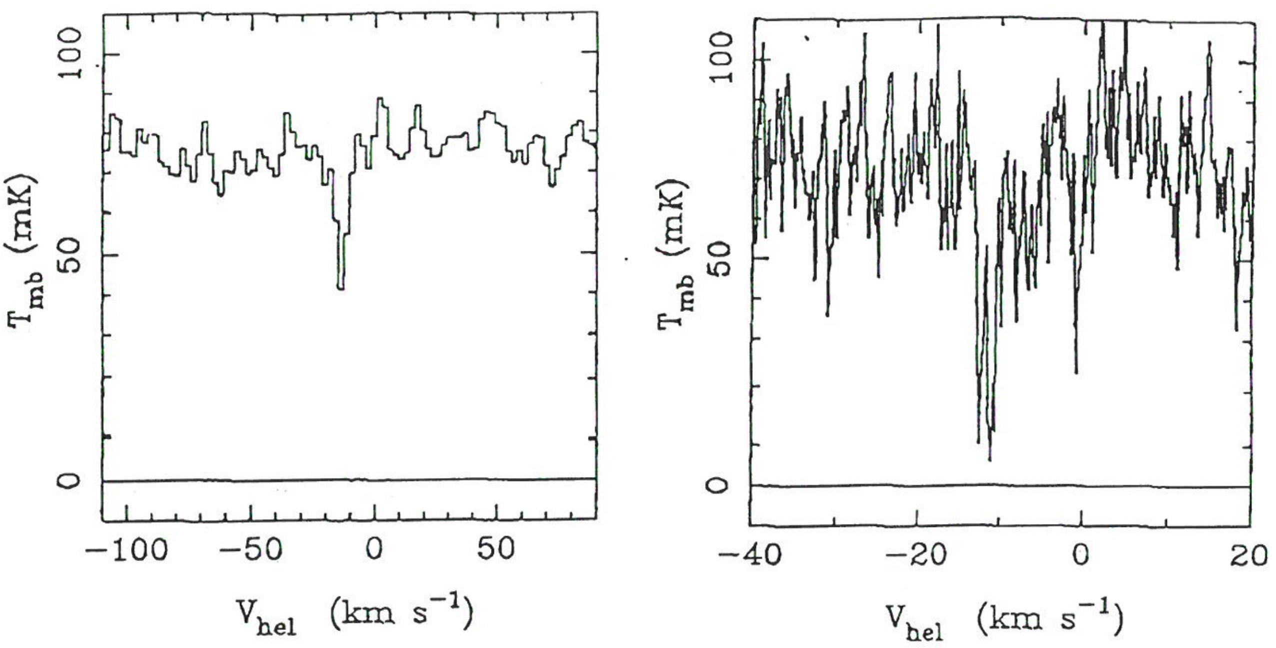
CO Emission and Absorption from High-Redshift Galaxies and Quasars
(T. Wiklind)

It is only recently that it has been appreciated that cosmological corrections render CO emission at high redshifts more easily detectable than a simple Euclidian geometry would suggest. Nevertheless, the amount of molecular gas required for a detection with present day instrumentaion is enormous. Despite this there have been observations of CO emission from the galaxy F10214+4724 at a redshift of $z = 2.3$, with an inferred mass of molecular gas of $\sim 2 \times 10^{11}\ M_\odot$. Radio quiet QSOs as well as giant radio galaxies have also been shown to have relatively large amounts of molecular gas, detectable through CO emission.

Molecular gas is invariably associated with star formation activity, and the detection of large amounts of such gas at high redshifts suggests that we are witnessing epochs of major star formation activity in these distant galaxies. In the case of F10214+4724, it may well be the first such epoch, involving a transformation of a mainly gaseous object into one composed mainly of stars, i.e. the formation of an elliptical galaxy. The presence of the tracer molecule CO as well as large amounts of dust implies that there has been a prior processing of the primordial gas. In the case of QSOs and giant radio galaxies, the presence of a gaseous interstellar medium is believed necessary for maintaining the enormous energy production in the center.

There have been searches for systems similar to F10214+4724 in their molecular gas properties using damped Lyman–α systems as diagnostics of high–z galaxies, or protogalaxies. Despite a few early tentative claims of CO emission there have not yet been any confirmed detections. The claimed detection of $\sim 10^{12}\ M_\odot$ of H_2 in the $z = 2.14$ damped Lyman–α system towards the QSO 0528–250 was not verified by more sensitive observations made with the SEST. The result from these surveys tell us that the damped Lyman–α systems are not similar to the hyperluminous galaxies of the type F10214+4724, but the limits to the molecular gas mass are still relatively high and do not rule out star bursting systems similar to Arp 220. However, damped–Lyman–α systems only represent one type of galactic objects at high redshifts, selected because their redshifts can be well determined optically.

Figure 5



^{12}CO(0-1) absorption lines seen towards the background source PKS~1413+135. The absorption arises in an intervening spiral galaxy at a redshift of z=0.247. It is not yet clear if the background source, a BL Lac object, is associated with the spiral galaxy, or if it is a chance projection. The left figure shows the absorption as sen in the low resolution spectrograph (4.5 km/s) and, the right in the high resolution one (0.26 km/s). The CO data was obtained with the SEST in December 1993. Subsequent observations have shown considerable changes in the structure of the absorption lines.

A different approach to the study of molecular gas at high redshifts is to observe molecular absorption, rather than emission lines. Flat spectrum radio loud QSOs provide a background continuum where galaxies, either associated with the QSO itself or intervening systems, produce absorption. The advantage with this kind of study is that the sensitivity is a factor 10^{10} higher than in emission line studies. Also, it allows a detailed study of the small scale structure of the interstellar medium in the absorbing galaxies, only limited by the extent of the background source. The hitherto only known such absorption system was detected with SEST in December 1993, and has allowed a detailed study of the molecular gas content of a spiral galaxy at a redshift of $z = 0.25$ (fig. 5). Several molecules and transitions have been studied, some that have never before been observed in nearby objects, due to the transition frequencies falling in atmospheric absorption bands. The high redshift of the absorbing galaxy shifts the transitions into transparent parts of the atmosphere. Another interesting feature of this type of high redshift object is the rapid variability of the absorption lines. The absorption system in the newly discovered $z = 0.25$ system has undergone considerable changes on a time scale of 2 months. The nature of these changes is not clear at present, but could represent extremely small scale structure in the interstellar medium of the redshifted galaxy.

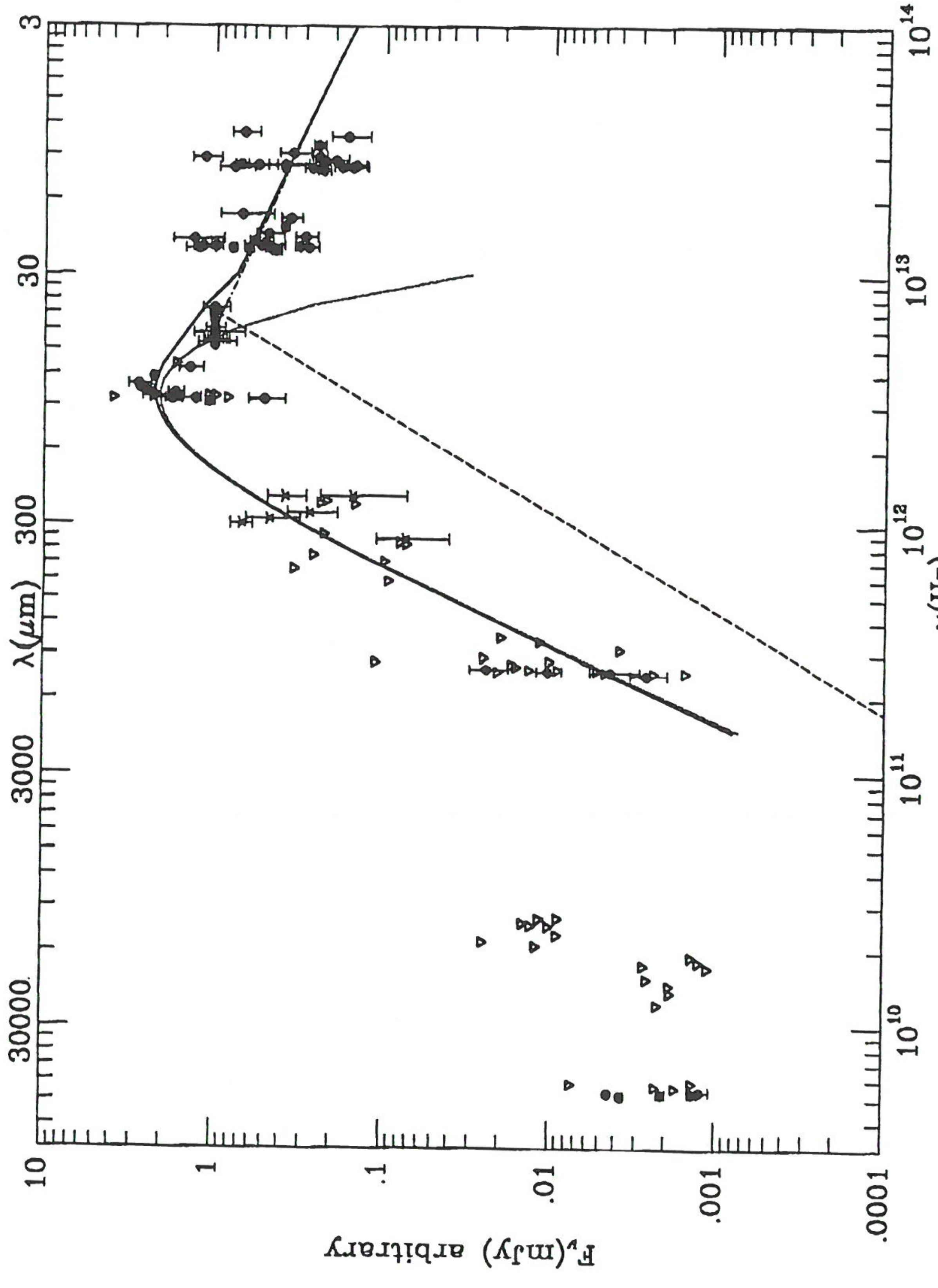
1.25 mm Observations of high-redshift QSOs
(P. Andreani et al.)

The continuum emission at 1.25 *mm* of 10 high-redshift ($z > 3$) and 10 intermediate redshift ($1.5 < z < 3$) quasars previously observed at 6 *cm* with the VLA have been carried out with the MPIfR ^{3}He bolometer during September 1991 and 1992. Because of the extraordinary atmospheric stability, we were most of the time constrained only by the detector noise. This turned out to be less than 140 mJy/$\sqrt{Hz}$.

Each source has been observed three times for $200{\cdot}n$ s, with n ranging between 8 and 10. 4 detections at a level better than 3σ and 3 marginal ones (2.8σ and 2σ) have been achieved. On the basis of these data it is possible to investigate the expected turn-over of the AGN sub*mm* spectrum, since in the quasar rest frame the 1.25 *mm* continuum corresponds to emission around 230-500 μm. As far as radio-quiet objects are concerned, the mechanism responsible for part of this emission is very likely thermal and can be ascribed to dust grains. It is very likely that this dust belongs to the quasar host galaxies, implying evidence for cold dust in these galaxies. The extinction caused by this dust could account for the higher spectral indices of the UV spectrum of the detected objects with respect to the non-detected ones.

Figure 6 shows a composite FIR/mm/radio spectrum of our sample plus the sample of 26 radio-quiet objects observed by Chini et al. (1989, A&A, 219, 87-97, 1989, A&A, 221, L3-L6) at 1.3 *mm*, built with the assumption that radio-quiet quasars represent a single population. We have discarded all sources with 6*cm* power greater than 10^{25} W/m^2/sr. The spectrum has been constructed in the quasar rest frames by scaling all the fluxes to the *same distance* and shifting the frequency according to the quasar redshift. The fluxes of the objects having a 60 μm detection have been normalized to the scaled 60 μm flux, the other ones to their absolute blue flux and then multiplied by the average ratio $\frac{F_B}{F_{60\mu m}}$

Figure 6


λ(μm)
3
30
300
3000
30000
ν(Hz)
10^14
10^13
10^12
10^11
10^10
F_ν(mJy) arbitrary
10
1
.1
.01
.001
.0001

determined with the first objects. The filled circles represent data taken from Chini et al., open triangles upper limits, stars the detections discussed in our work. The solid line is a convolution of the following components: a power-law spectrum $F(\nu) \propto (\nu/\nu_0)^{5/2}$ emitted by a homogeneous synchrotron source (dashed line), a $F(\nu) \propto \nu^{-0.7}$ curve (dot-dashed), a thermal curve, $\lambda^{-\alpha} BB(\lambda, T_d)$, with $\alpha = 2$ and $T_d = 20$ K (dotted).

These data have been used also to infer upper limits on the sky fluctuations at angular scales of 70″ and 140″ (Andreani, ApJ 1994, in press) . It is found that $\frac{\Delta T}{T} < 2.4\ 10^{-4}$ at 70″, $\frac{\Delta T}{T} < 1.9\ 10^{-4}$ at 140″, (95 % confidence level) for uncorrelated patches of sky. The former limit is 10 % higher if detections of radio-quiet objects are included in the analysis. These limits can be used in the context of: (1) models predicting far-infrared cosmic backgrounds originated from primeval dust and (2) models of dusty galaxy evolution. On the basis of these data most of the primeval dust models can be ruled out and further constraints on the galaxy population contributing to the background can be determined.

Continuum observations of AGN

(R. Booth)

Flux density variations in AGN are one of their fundamental problems while being at the same time one of the main ways of investigating their true nature. It is therefore important to monitor the flux variations of AGN at all wavelengths.

In the radio wavelength spectral regime, high frequency monitoring observations are necessary for several reasons. The innermost cores of AGN typically become transparent at frequencies above 15 GHz, where one also expects the differences between the various classes of sources to be most noticeable. The flux variations are both larger and more rapid, and the outbursts are much better resolved than at longer wavelengths, where flares are self absorbed and time delayed so that they often merge together. Because of the relatively high time resolution at millimetre wavelengths it is possible to study the detailed time history of an outburst, from growth to decay.

Data from the optically thin radio regime is also of interest for comparison with variability at other wavelengths where emission is thought to be associated with the nuclear region. Specifically it has been found that in some sources, time lags between the radio events and those detected at optical and X-ray wavelengths are very small, even zero, making possible the connection of the events at these wavelengths.

Finally, high frequency continuum monitoring complements millimetre and space VLBI observations, not only by identifying suitable targets with small (rapidly varying) components, but by providing advance warnings of new outbursts about to descend to VLBI frequencies, and by helping to place the VLBI snapshots in their correct context in the time history of the source.

Continuum observations with SEST were begun not only to monitor variable sources but also in an attempt to find continuum positional and flux density calibrators in the southern sky, not previously observed at millimetre wavelengths. With the exception of Cen A the search has not been too fruitful so far. However, as is predictable, the sources detected in the TIDRIS Space VLBI experiments as having brightness temperatures exceeding 10^{12} K, were found to be among the strongest at 100 GHz.

The most consistent programme of continuum monitoring with SEST has been that of the Finnish group from the Helsinki University of Technology. They have combined SEST data at 1.3 and 3 mm with longer wavelength (22 and 37 GHz) data from a dedicated programme at the Metsahovi Radio Research Station. Another important series of observations interleaved with this programme is a more frequent monitoring programme on 3C 273 by Couvoisier et al.

Some important facts to emerge from the monitoring programmes are described below. From detailed multi-wavelength observations of 3C 373 it is observed that there is a rich variety of behaviour, both within single wavebands and in different spectral regions. a specific and puzzling result is a clear decoupling between the X-ray emission and the other emission components. This is unexpected in synchrotron self-Compton models, it is also unexpected if the X-rays come from deep in the potential well. This decoupling shows that the X-ray emission comes from a region with its own intrinsic variability. This is in contrast to studies of BL Lac which have shown that the X-ray and infrared-sub millimetre regions vary together, in support of the syncrotron-Compton model.

Specific to the wider millimetre monitoring programme, many sources (50%) in the samples studied have experienced outbursts of such rapidity that the component brightness temperature exceeded the Compton limit, $T_b > 10^{12}$, implying relativistic boosting. The T_b distributions for various classes of AGN are different, with highly polarised quasars generally having the highest brightness temperatures followed by low polarisation (ordinary) quasars and finally radio galaxies. It has been shown that the typical variability may be explained in terms of a generalised shocked jet model based on the suggestion of Marscher and Gear (1985), in connection with the unified model of AGN, in which the beaming direction relative to the line of sight (viewing angle) determines the observed nature of the source.

Although these general conclusions hold, there are considerable differences from source to source and unexplained smaller scale variations on all time scales and at all frequencies. More statistics and more detailed observations are required for a full understanding of the variability problem.

VLBI at Millimeter Wavelengths

(R. Booth)

Although very long baseline interferometry, VLBI, at millimetre wavelengths is sensitivity limited, pioneering observations at wavelengths of 3 and 7 mm have shown it to be valuable as a probe to investigate the cores of quasars and radio galaxies on the very smallest measurable scales. This work has been very successful and it is now possible to produce images with resolutions (up to 50 micro-arcseconds at 100 GHz) superior to those attainable by any other astronomical technique and surpassing the HST by two orders of magnitude.

Recent results have also shown that millimetre VLBI has important applications in Galactic astronomy. The radio source Sgr A* in the Galactic centre has recently been imaged with the VLBA at 7mm and shown to have dimensions greater than the scattering size seen at longer wavelengths. Furthermore, contrary to earlier observational results, it has been shown that the SiO masers are unresolved on long (trans-European) baselines. Since these masers are believed to be excited in the photospheres of evolved stars, their study should provide important insights into this region of the star.

Millimetre VLBI of Extragalactic Radio Sources. One of the most challenging tasks of extragalactic astrophysics is the investigation of the powerful Active Galactic Nuclei, AGN. These objects generate as much as 10^{48} erg/sec in a volume as small as a planetary system and are thought to be powered by mass accretion on to a black hole. The only technique with a resolution approaching that required for these studies is VLBI and the extension to observations at the shortest manageable wavelengths with the longest available baselines is imperative if we are to fully understand the phenomena involved.

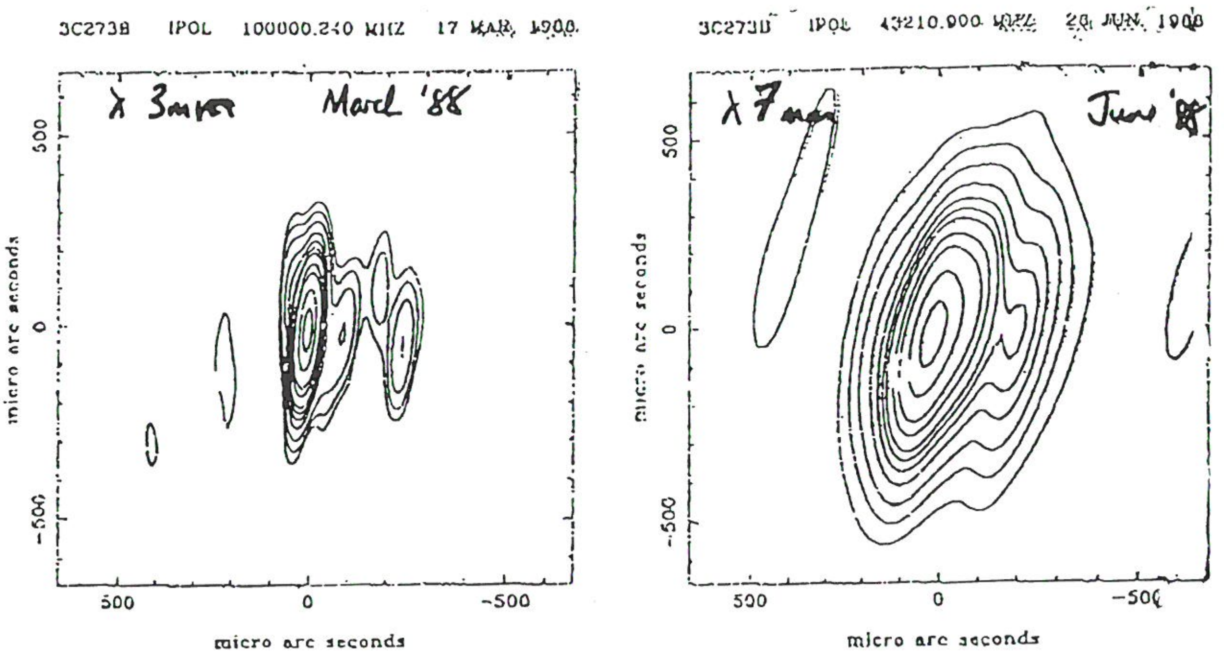
This extension is important because:

1. The resolution provided by millimetre VLBI enables us to study the closer AGN on scales of 10^{17} cm; scales comparable with the predicted size of the accretion disc around a 10^9 $M_\odot$ black hole. It also enables studies of more distant objects on scales of order 1pc.
2. The high resolution coupled with the fact that at these high frequencies the cores are optically thin means that observations can be used to probe the cores of the AGN much more thoroughly than with similar resolution at longer wavelengths.
3. The radio emission regions at frequencies $>$ 20 GHz are comparable in size to the broad line emission regions. Thus a knowledge of the radio structure combined with optical continuum and spectral data should help to determine the physical nature of the energy source.
4. Many strong millimetre sources are also strong X-ray emitters. This may imply even smaller dimensions for the millimetre emission region.
5. The superluminal phenomenon seen at longer wavelengths in a number of AGN is thought to be related to the millimetre flux outbursts seen in the same objects. Millimetre VLBI observations with resolutions of light days or weeks can follow the outburst almost from its inception out to the inner jet.

The extragalactic observational programme. To date millimetre VLBI has been conducted with an array of six antennae: Onsala (20m), Effelsberg (60m equiv. at 7 mm), Haystack (36m), Maryland Point (26m), Quabbin (14m), Kitt Peak (12 m), Owens Valley (mm array), Berkley (mm array) and Nobeyama (45m). The SEST antenna and the IRAM 30m dish on Pico Valeta have also successfully been used. A large proportion of these telescopes will soon form a millimetre VLBI array with regularly organised observing sessions.

Results for 3C273. The quasar 3C273 (z=0.158) underwent a strong, rapid flux density outburst in March 1988, observed first in the infrared/optical wavebands and subsequently

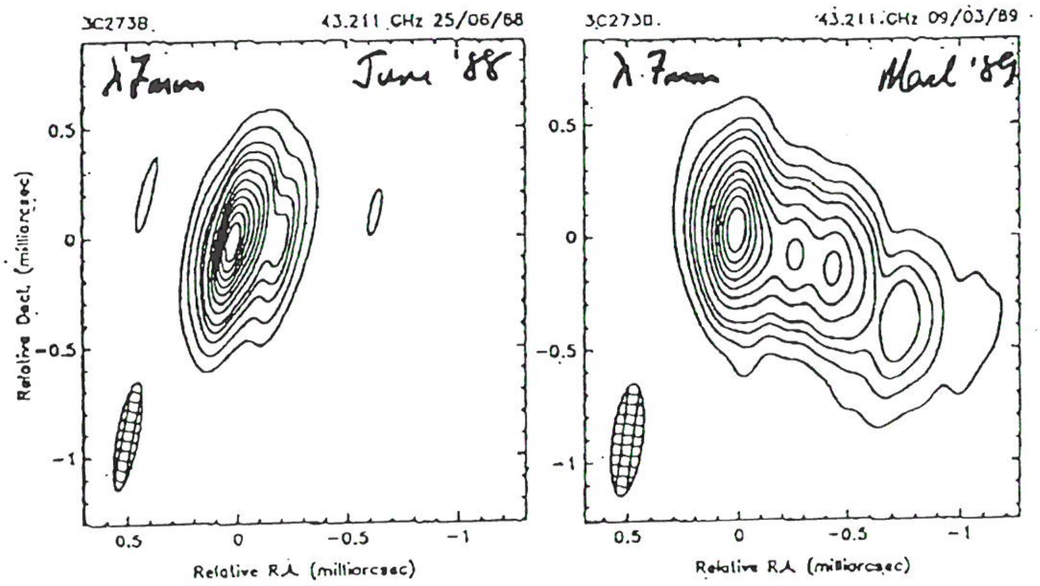
Figure 7



(a) (b)

Figure 7 a) 100 GHz and b) 43 GHz VLBI maps of 3C273 in March and June 1988, following a large outburst in the source. Both maps are plotted with the same scale.

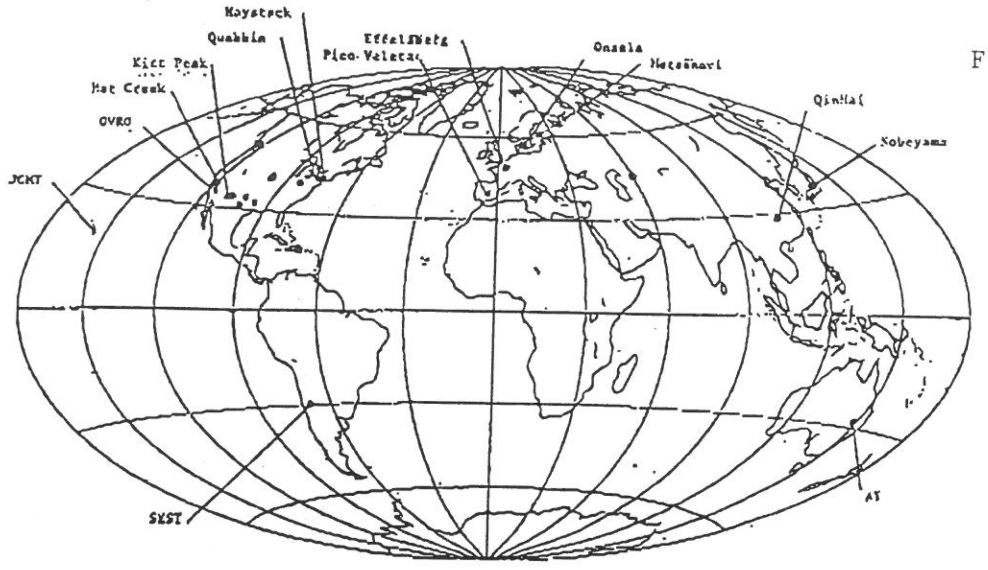
Figure 8



(a) (b)

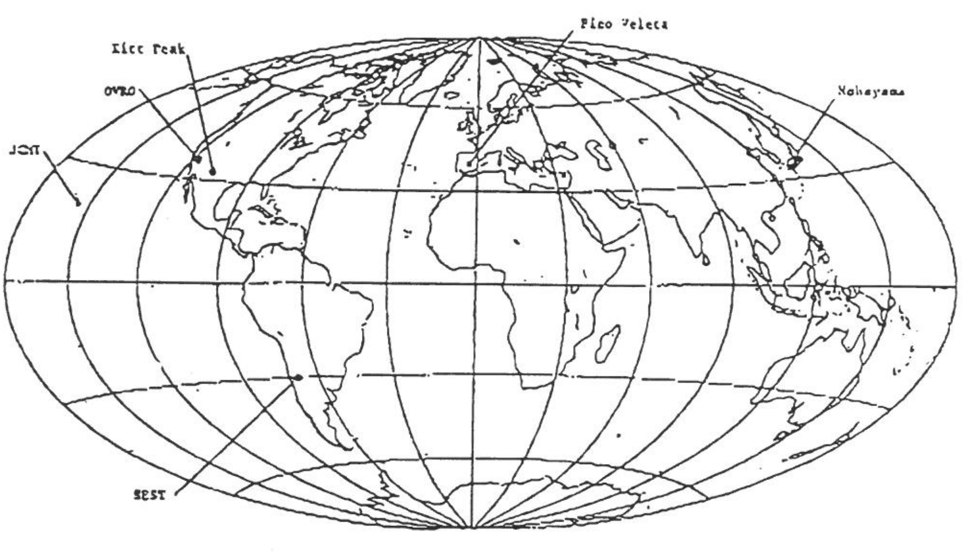
Figure 8: 43 GHz VLBI maps of 3C273 in a) June 1988 and b) March 1989 Both maps are plotted on the same scale. (Note that the scale is a factor of two smaller than that of the maps in Figure 1).

Figure 9



Telescopes available at λ3mm. Dots without label refer to VLBA antennas.

Antenna	diameter	eff.	S_{sys}	experiment
Nobeyama	45	0.30	1500	88,89,90
Onsala	20	0.48	5400	88,89,90,92
Owens Valley	3×10.4	0.60	2700	88,89
Hat Creek	3×6.1	0.60	13000	88,89,90
Kitt Peak	12	0.60	8000	88,89,90
Quabbin	14	0.50	8700	88
SEST	15	0.60	3900	90
JCMT	15	0.60	3700	planned 93
Pico Veleta	30	0.50	1200	92
Haystack	37	0.15	4200	planned 93
Effelsberg	60	0.10	2500	92
Metsähovi	14	0.30	18000	
Quing Hai	14	0.30	15000	



Telescopes available at λ1mm.

Figure 10

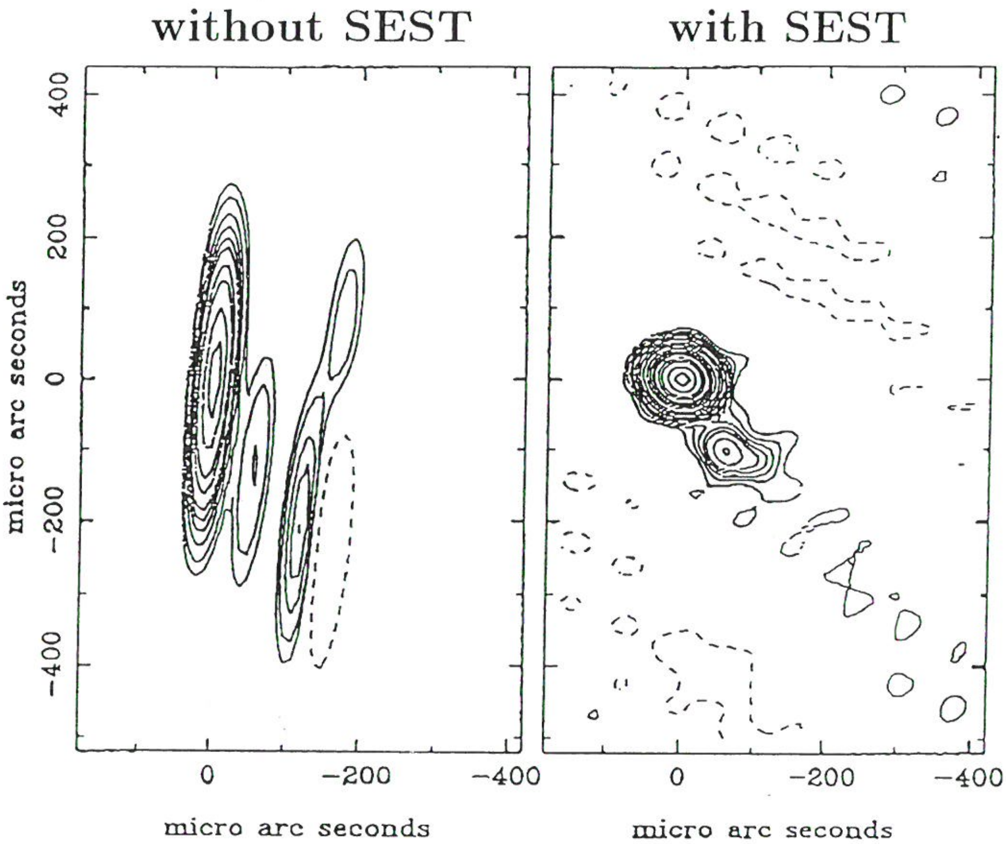


Figure 10 The radio jet of the blazar 3C279 observed with global VLBI arrays at 100GHz in March 1989 (right) and April 1990 (lower). Restoring beams were 280x50 μas in 1989 and 50x50 μas in 1990.

in the millimetre regime; the time delay between the maximum flux density in the optical and at 37 GHz was 6 months. At millimetre wavelengths the rise-time from the beginning of the outburst to its maximum leads to brightness temperatures exceeding 10^{12}K (at 90 GHz, an increase in flux density by a factor of 1.5 was recorded in a time of 24 days implying a brightness temperature $T_B = 10^{13}$K). VLBI observations were made at several points during the outburst; 7mm at 1988.48 and 1989.19 and 3mm at 1988.21 just after its onset (see Krichbaum et al, 1990 and Baath et al, 1991). The resulting maps are shown in figures 7 and 8. The upper pair of maps (Figs 7a & 7b) are those at 100 GHz, epoch 1988.2 and 43 Ghz at epoch 1988.48, plotted with the same scale. The lower pair (Figs 8a & 8b) are the two 43 GHz maps plotted on a reduced scale. These are the first ever micro-arcsecond observations of an outburst and reveal a wealth of detail, impossible to observe in any other way. They show that the structure within 1.5×10^{18} cm of the core (Fig 7a) is complex and has a position angle significantly different from that observed at longer wavelengths, further from the core. A comparison with the 7 mm map taken some 3 months later (Fig 7b) shows that the main component has travelled with an apparent speed of 0.8 milli-arcseconds per year. The apparent linear velocity is superluminal (5.5 c) and the component is therefore probably travelling almost directly towards the observer.

The SEST is a very important addition in this work. Almost all of the telescopes used for millimeter VLBI are located in the northern hemisphere (fig. 9), and the improvement for low-declination sources resulting from the addition of north-south baslines to the SEST can be dramatic, as shown in fig. 10.

It might also be added that VLBI is important for geodesy, and the location of the SEST in one of the world's most active areas is of obvious interest in connection with plate tectonics. The first VLBI observations involving South America were made using the SEST, in collaboration with the NASA Crustal Dynamics project, in 1990, and the position of the SEST telescope was determined to an accuracy of 2 cm in the geocentric coordinate system defined by the major VLBI telescopes.

Molecular Line Observations of Nearby Galaxies
(R. Booth)

The first extragalactic molecule to be detected was OH, observed in absorption against the nuclear continuum sources in M82 and NGC 253 by Weliachew in 1971. Since that time more than 20 extragalactic molecules have been detected and there is every reason to believe that external galaxies will exhibit the same chemical complexity as the Milky Way. Despite this complexity of molecular content, by far the most important results to date have come from observations of the relatively simple carbon monoxide molecule. CO is believed to be a good tracer of the most abundant molecule, molecular hydrogen, which is itself observed only under extreme excitation conditions. (H_2 has no permanent electric dipole moment and the lowest quadrapole rotational transitions lie in the infrared). Thus, over the past fifteen years, CO observations have been used to probe the molecular content of hundreds of galaxies, including one at the unlikely redshift of z=2.4! This, and several other detections of CO at high redshift, imply that molecules in external galaxies may be used as cosmological probes and that the volume of the universe available for study through CO observations is vastly greater than hitherto imagined.

The studies of molecules in galaxies include both detailed analyses of nearby galaxies and statistical comparisons of the global properties of selected samples of galaxies. These two approaches are complementary, and both are necessary to improve our understanding of the large scale processes that govern star formation and molecular cloud evolution. Both approaches have been taken with SEST.

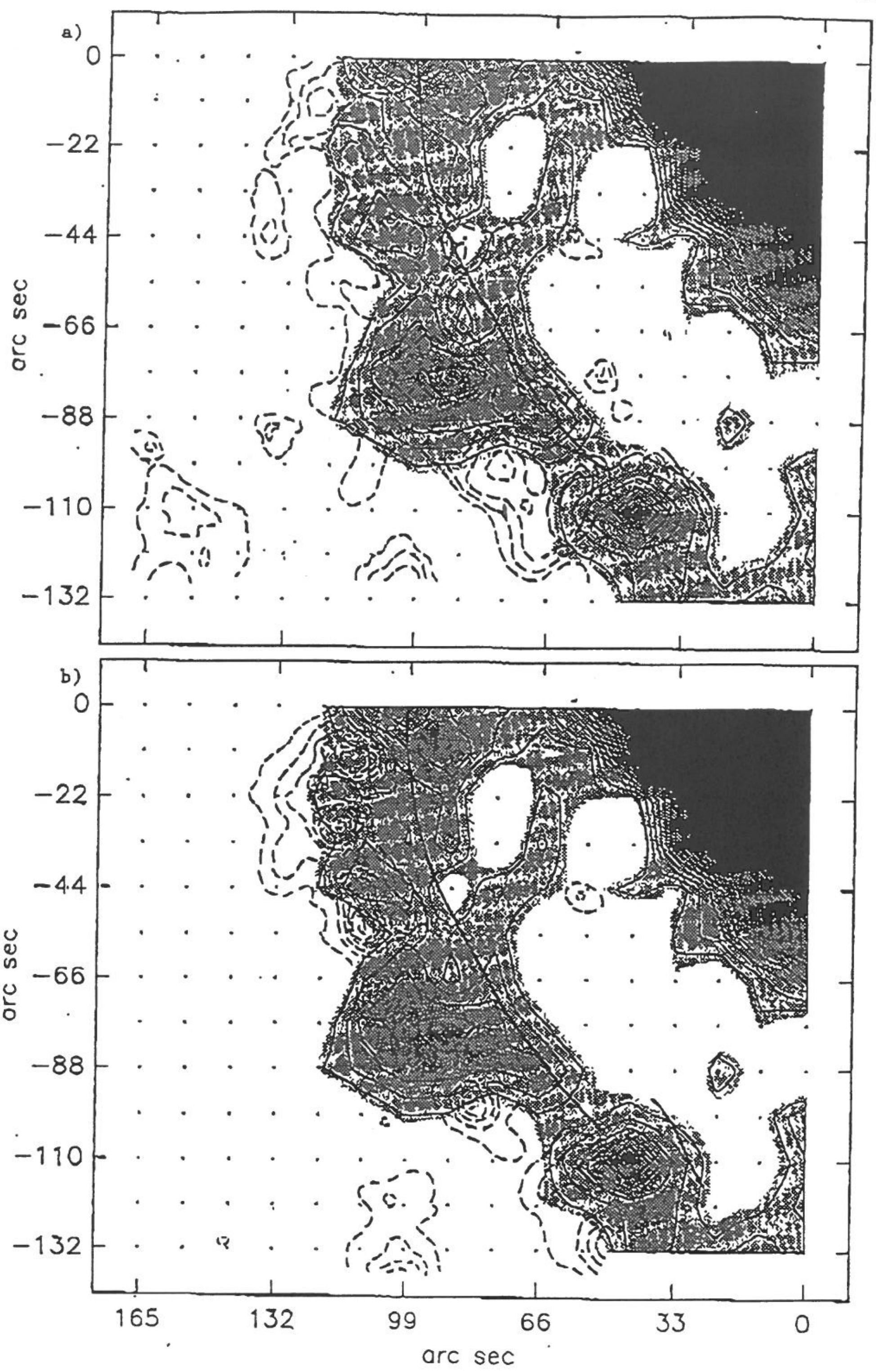
CO as a Tracer of Molecular Gas. Of course, the main molecular constituent of galaxies is molecular hydrogen, H_2 and so it is essential to be able to convert from the CO emission data to the molecular hydrogen mass in order to interpret the molecular data in terms of star formation rate and efficiency, etc. The exact conversion factor is controversial and SEST has been able to throw some valuable light on the origin of the controversy through observations of the Magellanic Clouds (MC) which are close enough for us to isolate Galactic sized molecular clouds. Because the MC have low metallicities and therefore relatively little dust, selective photodissociation of CO means that it is depleted relative to molecular hydrogen, which is self-shielding. Thus, the CO and molecular hydrogen may not even occupy the same spatial volume in low metallicity systems and the 'standard' Galactic conversion factor may well be meaningless under these conditions. The measured conversion factor in the MC is not much greater than for Galactic molecular clouds (x 3-5) but this must be for the molecular hydrogen in the CO regions and cannot represent that outside the CO clouds.

Individual Galaxies. The southern sky contains many unique and fascinating galaxies as well as remarkable examples of the standard types. SEST studies of M83 (fig. 11) have revealed a close similarity between the maximum CO contours and the spiral arms and a clear arm-interarm contrast. The spiral arm gas has been shown to be denser and to have a considerably smaller velocity dispersion than the inter-arm gas, in line with theoretical predictions.

The interacting (merging) systems NGC 3256, NGC 1808 and NGC 4945 have been studied in detail through multi-transition CO observations. It has become clear that the gas in the centre of these starbursting galaxies is considerably warmer than that in Galactic GMCs and that photodissociation through UV light released by the starburst is playing a major role in shaping the physical conditions, even in the molecular gas. In NGC 1808 and other active nuclei, modelling of the data implies a two component gas: a warm (50-100 K) more diffuse gas surrounding denser clumps of cooler gas. The warm CO is strongly associated with ionised carbon regions, which are also signatures of photon dominated regions.

Finally, among these examples, the nearest AGN, Centaurus A has been an important target for SEST. Here, CO was detected in absorption for the first time, against the nuclear continuum radiation, and the CO gas has been shown to delineate a disc in the centre of the galaxy, which lies orthogonal to the radio continuum jet. Is molecular gas streaming into the nucleus and feeding the central black hole?

CO Surveys of Galaxies. The statistical approach has yielded important results. Different large samples of galaxies have been searched for CO emission which, somewhat



CO(1-0) emission from a prominent spiral arm segment in the barred grand-design galaxy M83. The CO emission is represented by full-drawn contours and grey-scale. In the top figure the CO emission is compared with 21 cm HI emission (VLA) and in the bottom figure with Hβ emission, dashed contours respectively.

unexpectedly, is detected in all principal morphological classes - even in early type galaxies, which therefore must have significant on-going star formation. The most frequently used sample, combined with various other selection criteria, are the galaxies detected by the IRAS satellite. These galaxies emit the bulk of their energy in the far infrared regime of the spectrum through a conversion of the UV radiation from young and massive stars by heated dust. The large far infrared excess emission is supposed to result from a powerful burst of star formation and there is a clear correlation between the FIR flux and the CO intensity. Galaxies not detected by IRAS, even interacting systems, are weak or undetectable in the CO lines.

Closer investigations of the morphology of the strong IRAS galaxies reveal that a large fraction are interacting galaxies. Quasars have been discovered to be associated with colliding galaxies and ellipticals are suspected to be remnants of merging systems. The more exotic IRAS galaxies with infrared luminosities approaching $10^{12} - 10^{13} L_{\odot}$ are suggested to be evolutionarily connected to quasars. Again, the vast quantities of molecular gas may be fuelling the putative nuclear black hole.

Extragalactic Chemistry. It is well known that CO(1-0) observations give only restricted information about the properties of the molecular gas, e.g. high density regions are generally masked and excitation temperature variations are not easily detected from these observations alone. Observations of less common isotopes of CO and high density tracers like HCN and CS, although significantly weaker and thus more time consuming, should improve this situation. Additionally, observations of lines from higher rotational transitions also improve the spatial resolution.

SEST observations of southern galaxies have improved and consolidated our knowledge of extragalactic molecules. An important contribution is a survey of molecular transitions in the Large Magellanic Cloud. To date, 9 molecules (including 16 isomers) have been detected: CO, CS, CN, SO, HCN, HNC, HCO^+, H_2CO, and C_3H_2. Most unexpectedly, the observed intensity ratio of CO to $C^{18}O$ exceeds the Galactic value by a factor greater than 10. This difference is probably a result of the lower dust content in the LMC relative to the Galaxy; dust normally shields the molecules against the dissociating UV radiation field. A careful analysis of the data has shown that the ^{12}C:^{13}C abundance ratio in the N 159 region of the LMC is close to 50.

Molecular line observations of Centaurus A
(G. Rydbeck)

At a distance of about 3 Mpc Centaurus A is a close neighbour as well as host to a number of phenomena which are essential to the physics and evolution of galaxies. Not surprisingly it is one of the most well studied objects in the sky. Since it is a southern galaxy, the SEST telescope is ideally suited and has been extensively used to study its millimeter wave emission and absorption.

Centaurus A harbours the closest active galactic nucleus (AGN), which is important since high resolution is the key to observations of phenomena leading to nuclear accretion. The

Figure 12

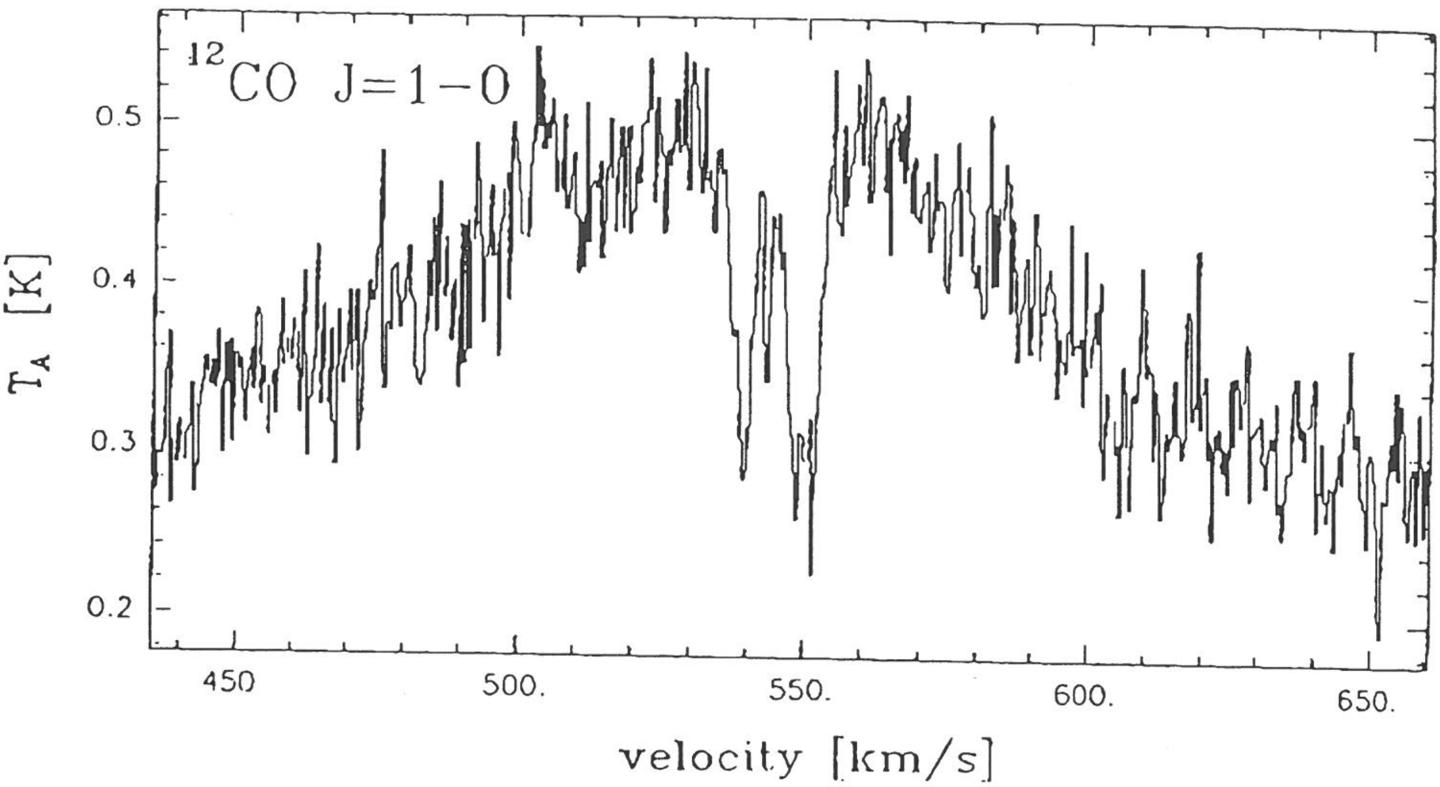
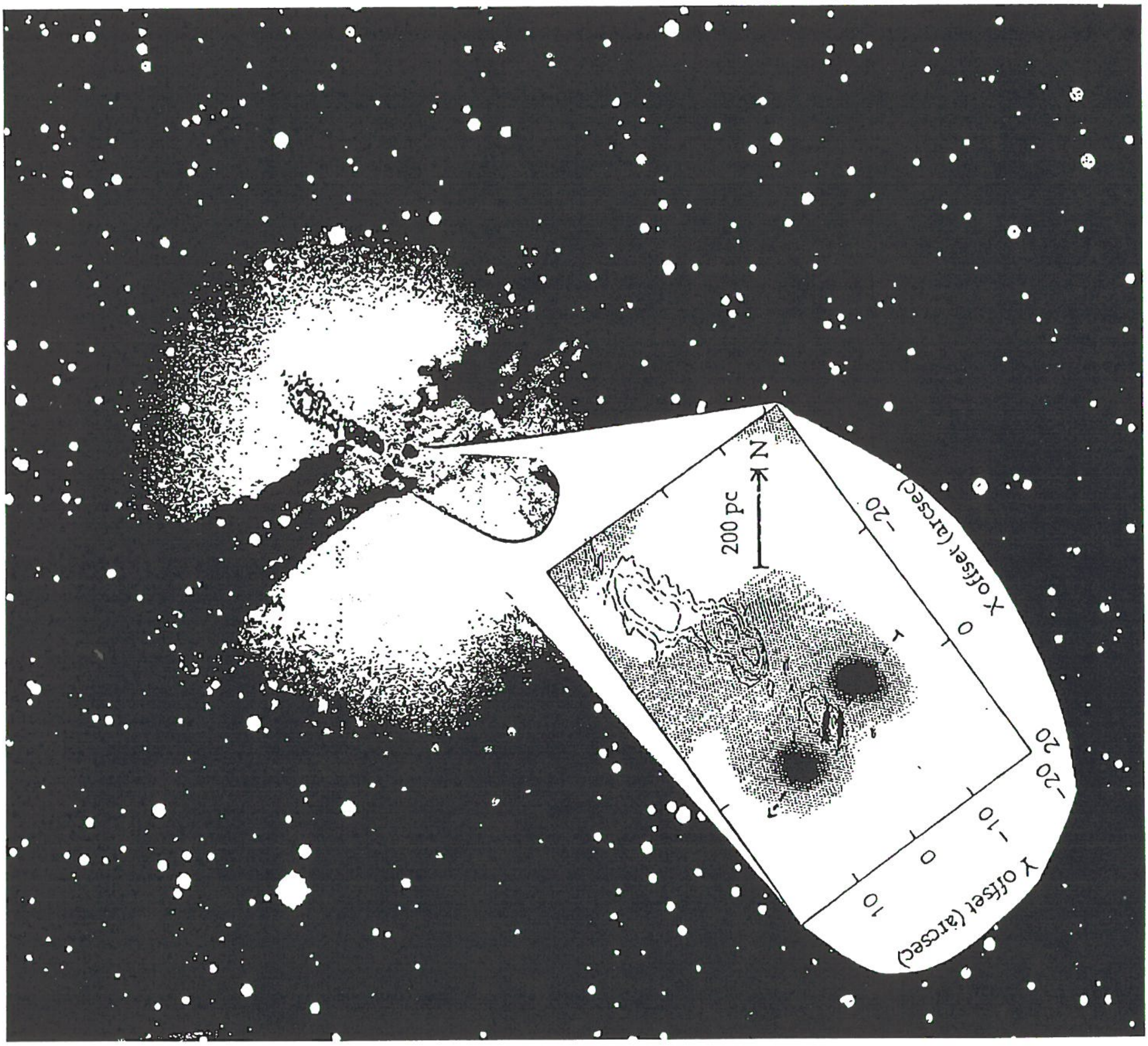


Figure 13



AGN reveals itself as a compact nuclear continuum source with jets extending from the core out to several arcminutes. An S-shaped dustlane, thought to be the remnant of a disk galaxy caught or partially caught by the original elliptical galaxy, streches across its nearly spherical distribution of stars. The nucleus is hidden behind this dustlane. Observationally this has two effects: i) The presence of gas in the dustlane gives rise to absorption lines in the nuclear continuum. Atomic (HI) absorption lines as well as a large number of molecular absorption lines (figure 12) have been reported in the literature (see e.g. Eckart *et al.* 1990 and Israel *et al.* 1990). ii) The AGN cannot be studied optically because it is hidden behind the dustlane. Recently one has seen X-ray filaments emanating from the nucleus. It has been suggested that this results from the AGN being a 'Blazar' hidden from our sight by the dust lane but irradiating clouds in the direction of the jets causing them to radiate in the X-ray regime.

The absorption lines, probably due to relatively few clouds at differing radial velocities, allow calculation of the physics in these clouds. It is however difficult to estimate their distance from the galaxy center. Eckart et al.(1990b) find that the clouds are cold (< 10 K), dense, and clumpy like typical dense galactic clouds. Simple estimates of properties from molecular emission lines from other parts of the galaxy give a similar result. There is some evidence that diffuse 'cirrus' clouds with large scale height (Eckart *et al.* 1990a) are responsible for a significant amount of the far IR emission.

Particular efforts have been made to make high signal to noise ratio studies of the galaxy center, first in CO(2-1) emission (Rydbeck et al. 1993) and later CO(3-2) emission. The central emission profile displays high velocity wings. Careful analysis shows that this high velocity emission originates in two 'blobs' situated symmetrically around the nucleus (fig. 13). The CO(3-2) image is preliminary and needs more signal to noise ratio but corobborates figure 13. The result can be interpreted as a molecular ring with a radius of 70 to 120 pc rotating at about 220 km s^{-1}. The ring is centered on the continuum source and aligned perpendicular to the radio and optical jet, which suggests that it is in fact feeding an inner accretion disk responsible for the AGN. The ring molecular mass can be estimated to 6 $10^6 M_\odot$, and the dynamical mass inside the ring is about 1.4 $10^9 M_\odot$.

Dust and Gas in Galaxies

(R. Chini)

The gas content M_{gas} of a galaxy is an important quantity because it provides the fuel for maintaining the luminosity either by thermal or non-thermal processes. Comparing M_{gas} with the infrared luminosity L_{IR} of a galaxy yields the efficiency of converting mass into luminosity. Generally, L_{IR} is dominated by the emission from dust heated by stars and hence L_{IR}/M_{gas} determines the efficiency of the global star formation. While L_{IR} is a rather straightforward observable quantity, the determination of M_{gas} requires measurements at FIR and mm wavelengths either in the continuum or in certain molecular transitions. We have started a systematic investigation of the gas content in two complete samples of 140 normal spirals and 49 active Markarian galaxies, respectively. Apart from some submm data obtained at the JCMT all results are based on 1300μm continuum measurements and CO $(2-1)/(1-0)$ observations from the IRAM 30m telescope and from SEST.

870 and 1300μm observations towards 46 Mkn galaxies selected from the *IRAS* catalog have yielded the following results (Krügel et al. 1988a,b ; Chini et al. 1989, 1992a) : i) In the wavelength range from 60 to 1300μm there is only one dust component with an average color temperature of 33 ± 5K; the wavelength dependence of dust opacity $m = 1.9 \pm 0.3$. ii) For the ratio of IR luminosity over gas mass, which is a measure of the star formation efficiency, a value of $L_{IR}/M_{gas} = 123 \pm 56$ in solar units is found. iii) A study of the radial distribution of the dust indicates that the major fraction of interstellar matter is concentrated within a galactocentric radius R of 3kpc. Using L_{IR} as a discriminator between individual galaxies, a dependence of M_{gas} on the radius R for three classes of luminosity can be derived. $M_{gas} \propto R^{\beta}$ with $\beta = 5.4$ for $R < 800$pc and $logL_{IR} = 10.2 \pm 0.1$, $\beta = 2.9$ for $R < 2000$pc and $logL_{IR} = 11.0 \pm 0.1$, and $\beta = 2.3$ at still larger distances for galaxies with $logL_{IR} = 11.4 \pm 0.1$. The high ratio L_{IR}/M_{gas} requires either a star burst with an efficiency of $\approx 35\%$ or an initial mass function that has shifted to stars with $m \geq 8M_{\odot}$. In Seyfert galaxies L_{IR}/M_{gas} is a factor of two lower than in comparable starburst galaxies.

The same sample of Mkn galaxies was also studied in the mm CO lines at the IRAM 30m telescope and at the SEST on La Silla (Krügel et al. 1990; Chini et al. 1992b). This gave the opportunity to compare gas masses derived from the dust emission with those from the CO luminosity. For 21 objects dust and CO measurements are available referring to a similar beam size of about 12", i.e. to the same area on the galaxy. Here the two methods agree rather well. By comparing CO lines of different beams it was found that the molecular gas is concentrated towards the center of the galaxies. (Note that the SEST and the IRAM 30-m telescopes, because of the factor of two difference in size, complement each other for many studies: different beams with the same molecular transition give information on angular extent, and identical beams with different molecular transitions (*e.g.* CO (1-0) and CO (2-1)) facilitate analysis of the physical and chemical processes along a given line of sight).

First results for a subset of 34 non–active spirals mapped at 1300μm with the SEST bolometer have been obtained recently (Chini & Krügel 1993, Chini et al. 1994): i) The spatial extent of the cold dust is comparable to the optical size of the galaxies. About 70% of the mass is contained within half the optical radius; its distribution decreases roughly with $1/r$. ii) Combining the new observations with *IRAS* data and adopting a ν^2 dependence of the dust opacity a temperature of ≈ 21K is found for the coldest dust component; its emission dominates the wavelength range from 100 to 1300μm. iii) The ratio of infrared luminosity to gas mass L_{IR}/M_{gas} is 8 ± 3 in solar units and hence more than a factor of 10 lower than in active galaxies. iv) L_{IR}/M_{gas} is a signature for the stage of activity and allows a clear separation between normal spirals, active galaxies and quasars.

References

Chini R., Krügel E., Kreysa E., Gemünd H.–P., 1989, A&A 216, L5
Chini R., Krügel E., Kreysa E., 1992a, A&A 266, 177
Chini R., Krügel E., 1993, A&A 279, 385

Chini R., Krügel E., Lemke R., Ward-Thompson D., 1994, A&A (submitted)
Chini R., Krügel E., Steppe H., 1992b, A&A 255, 87
Krügel E., Chini R., Kreysa E., Sherwood W., 1988a, A&A 190, 47
Krügel E., Chini R., Kreysa E., Sherwood W., 1988b, A&A 193, L6
Krügel E., Steppe H., Chini R., 1990, A&A 229, 17

Normal and Interacting Galaxies observed with the SEST
(M. Gerin et al.)

The Gas Content of Normal and Cluster Galaxies. Cluster galaxies have generally less atomic gas as traced by the 21cm hyperfine structure line of HI than isolated galaxies. We have used the SEST to study the amount of molecular gas, traced by the J=1–0 rotational line of CO, for galaxies in the Fornax cluster. We have found that those galaxies, though having a normal content of atomic gas, have much less CO emission than expected. This work showed that the average CO emission of a given type of spiral galaxy is still unknown. We then have undertaken dedicated studies to determine the average gas content of spiral galaxies and to establish the reliability of the CO J=1–0 rotational line as a tracer of molecular hydrogen. With the SEST, we have observed recently about 50 spirals selected from the Karachentseva catalog of isolated galaxies. Their CO emission was surprisingly faint and well correlated with their FIR emission (based on IRAS data). Indeed, the comparison of gas masses derived from HI, CO and dust emission shows good agreement but a large scatter. CO emission is better correlated with the IRAS FIR emission and with the dust mass derived from the dust emission at 1.3mm detected with the SEST bolometer than is HI but a large scatter remains. Data with a better sensitivity both in the line and in the continuum maps are needed to settle this important topic.

Interacting galaxies. With an enhanced star formation rate and perturbed dynamics, interacting and merging galaxies present an extreme environment for molecular gas. Indeed we have shown that though the CO(J=1–0) line is very intense in such objects, the isotopic line ^{13}CO(J=1–0) is much weaker than in spirals. The lines are also broader than towards normal spiral galaxies and show less rotation. The detection of a large amount of molecular gas in the merger remnant NGC 7252 shows that the intense burst star formation which occurs in the first stages of the collision does not consume all the molecular gas. The peculiar line ratios suggest that the physical conditions in this gas are largely modified during the encounter and that some elemental abundances are altered by the gas ejected into the ISM by the stars born in the burst.

Ring galaxies are formed by the collision of a spiral galaxes and a compact companion passing nearly throug its disk. The target responds to this violent perturbation by forming stars in a coherent ring expanding in the disk. Using the SEST and the IRAM 30m telescope, we have observed about 19 galaxies and detected 4/5 of them. Most of these galaxies are very rich in molecular gas; one of the remaining undetected galaxies is the "Cartwheel Galaxy", archetype of this class of object. This galaxy is forming its first generation of star and probably had a low surface brightness before the interaction.

F. Casoli, C. Dupraz, F. Combes :" A molecular line survey of the merger NGC 3256" :

1992, A&A 264, 49.
F. Casoli, C. dupraz, F. Combes : "The case of missing ^{13}CO in mergers" : 1992, A&A 264, 55.
F. Casoli, C. Dupraz, F. Combes and I. Kazes : CO in mergers III NGC 1614 and NGC 3256 : 1991 A&A 251, 1.
C. Dupraz, F. Casoli, F. Combes and I. Kazes : CO in mergers II NGC 7252 : the link between mergers and ellipticals : 1990 A&A 228, L5.

Magellanic Clouds Key Programme
(F. Israel)

A major advantage of astronomical facilities in the southern hemisphere is the observational access they provide to the two nearest extragalactic systems: the Large and the Small Magellanic Cloud. Their proximity and our vantage point provide both high linear resolutions (not easily attainable on other galaxies) and a global view not hampered by high extinction and distance ambiguities (not attainable in the Milky Way Galaxy).

Studies of the interstellar medium and star formation processes in the Magellanic Clouds profit, in addition, from the differences in metallicity and star formation rate between the two Clouds themselves, and between the Clouds and the Milky Way. The different environments that can be studied with similar, high linear resolutions enable us to gauge the influence of radiation intensity, metallicity etc on the physics and chemistry of the ISM and on star formation to an extent not possible otherwise.

The SEST is the only millimeter telescope in the world with access to the Magellanic Clouds, and is thus essential to the type of investigation sketched above. The most important millimeter lines that can be observed with the SEST are those due to the lower transitions of the CO molecule, and its ^{13}CO and $C^{18}O$ isotopes. CO traces dense clouds of the much more abundant H_2 molecule; H_2 is with HI the major component of the ISM in galaxies. CO observations yield the location, distribution and kinematics of major star formation zones throughout the Magellanic Clouds. In addition, observation of CO and its isotopes in several transitions, combined with other information, such as the intensity of millimeter line emission from other molecules, far-infrared line emission from ions such as C^+, and continuum radiation at radio and infrared wavelengths, allows us to gain significant insight into the physical processes taking place in these dense molecular clouds as well as the processes that lead to, and accompany, the formation of stars. A major question is the relation between observed CO strength and actual H_2 column density in the Magellanic Clouds. Is the empirically determined value for the Milky Way also valid under the rather different conditions predominant in the Clouds?

At the time of its commissioning, several groups vying for observing time on the Magellanic Clouds were merged, and, because of the uniqueness and importance of the Magellanic Clouds, the work was given Key Programme status. This KP includes the Swedish observers. Thus, the ESO KP on CO in the Magellanic Clouds not only was the first ESO KP, but is also the only one that is a joint (ESO-Swedish) programme. The SEST beam at 2.6 mm (CO J=1-0) corresponds to a linear resolution of about 12 pc on the Clouds; at the J=2-1 transition this is about 6 pc. The LMC surface area is 300 000 SEST (2.6

mm) beams, the SMC about 30 000 beams. This means that complete mapping of the LMC would take 37 500 hours, or 8 hours daily, 13 years long. The SMC with its weaker emission would require at least 5 years of daily observing. Even a much more modest programme, concentrating on specific areas thus clearly required the joint, major effort that could only be realized in the Key Programme concept.

Most of the intended mapping in the CO J=1-0 transition has now been completed. Based on the resuilts of this mapping, regions were selected for further observation in the J=2-1 transition, and the ^{13}CO isotopes. It very quickly became clear that multi-isotope, multi-transition information is essential to any attempt to model the physical condition of the molecular gas, and this effort is still continuing.

In the LMC large fields have been mapped in and near 30 Doradus, but by no means the whole complex. The star formation regions associated with the Henize HII regions N11, N55, N57 and N59 have also been mapped.; the HII region N44 is still to be done. In order to obtain a more general impression of the distribution and condition of CO in the LMC a survey of over 100 IRAS sources has been conducted, and two one-dimensional strips (one north south, one east-west) through the LMC have been mapped. In the SMC a number of smaller fields have been studied in the crowded and confused southwest part of the Bar, as well as fields containing the Henize HII regions N66, N81 and N88. Some fields remain to be done. So far, most of the effort has gone into obtaining the data, which is especially slow going in the J=2-1 transition, because of the smaller beams and problems encountered with the receiver. However, several papers either have already appeared, are in press, or are almost finished. Observations have also been made in service mode for colleagues not part of the Key Programme.

The results are very interesting. As expected, CO emissivities are much lower than in the Milky Way, by about a factor three in the LMC, and about an order of magnitude in the SMC. There is generally a good correlation between the occurrence of CO and the presence of IRAS sources. CO interclump gas, usually seen in Galactic sources, is mostly missing, nor have we found diffuse CO clouds not associated with star formation regions. Also, the clumps observed in the Clouds have a tendency to be smaller than those seen in comparable Galactic sources. Model calculations indicate that at the Magellanic Cloud radiation field intensities and metallicities, CO dissociation by energetic photons is a major effect, much more so than in the Galaxy. As we can estimate the radiation field intensity in the Clouds reasonably well, it is of great interest to compare CO results obtained towards regions with similar metallicity, but rather different radiation field intensities. A first attempt to do so indeed shows surprisingly clear differences between molecular cloud complexes in such different environments.

In line with these differences is the finding that quiescent molecular cloud complexes in the LMC exhibit a relationship between cloud size and linewidth that is similar to, but offset from the same relationship found for outer Galaxy molecular cloud complexes in the sense that for the same linewidth, quiescent molecular clouds in the LMC are smaller by a factor of three or so. In stark contrast, clouds in the active LMC complex N11 define a relationship that is very steep: size increases by a factor of two are accompanied by linewidth increases by a factor of five instead of the quiescent linewidth increase of

25%. This significant quantitative difference must contain an important clue to the physical structure of molecular cloud complexes under different environmental conditions, but without the planned modelling no firm conclusion can yet be drawn.

A particularly interesting case is the molecular cloud complex associated with the second largest LMC HII region N11, which contains several Lucke and Hodge OB associations, of various ages and richness. About two dozen CO clouds, each about 40 pc is size are distributed throughout the complex; no intercloud gas is seen. Several molecular clouds are at the periphery of an optical shell, centered on the richest OB association. Comparison of the CO in this complex and others with far-infrared line (C^+) and continuum maps at similar resolution shows that the photon-dominated zones, traced by C^+, contain masses that are of the order of, or larger than, the estimated molecular mass. The good correlation between C^+ and far-infrared dust emission on the one hand, and the generally much poorer correlation between C^+ and CO on the other hand, clearly illustrate the great range of radiation field intensities even over scales of 100 pc, and allow good estimates to be used in the analysis of the CO results.

More quantitative analysis of the astrophysical conditions awaits completion of the J=2-1 measurements in particular, and the use of these in the existing models of dense clouds.

Recent Publications from the ESO-SEST Key Programme: CO in the Magellanic Clouds:

Rubio, Lequeux, Boulanger, Booth, de Graauw, Israel, Johansson, Kutner, Nyman 1993 A&A 271, 1-8 II. CO Clouds in the SMC SW Bar

Rubio, Lequeux, Boulanger 1993 A&A 271 9-19 III. Molecular Gas in the Small Magellanic Cloud

Israel, Johansson, Lequeux, Booth, Nyman, Crane, Rubio, de Graauw, Kutner, Gredel, Boulanger, Garay, Westerlund 1993 A&A 276, 25-40 I. A Survey of CO in the LMC and the SMC

Lequeux, Le Bourlot, Pineau des Forets, Roueff, Boulanger, Rubio 1994 A&A submitted Physical Properties of Molecular Clouds in the Small Magellanic Cloud

de Graauw, Israel, Johansson, Booth, Boulanger, Garay, Kutner, Lequeux, Nyman, Rubio 1994 A&A in preparation CO in the Giant LMC HII Region Complex N11

Heydari-Malayeri, Lecavelier des Etangs 1994 A&A submitted The LMC HII Region N4A and its Unusual Molecular Cloud (observations done in KP service mode)

SN 1987A in the Large Magellanic Cloud.

The SEST has contributed important data in the study of the supernova SN 1987A in the LMC. Bolometer observations at 1.3 mm provide the only wavelength now observed between 10-20μm and the radio range. A series of observations give a consistent flux density of $\sim$ 8-9 mJy; a slight increase with time cannot be ruled out. These detections suggest that free-free emission is probably contributing to the energy spectrum (Bouchet *et al.*, 1991 Astron. J. **102**, 1135 - see fig. 14). Observations in the (sub)millimeter region may eventually be the only means of monitoring the evolution of dust in the SN envelope.

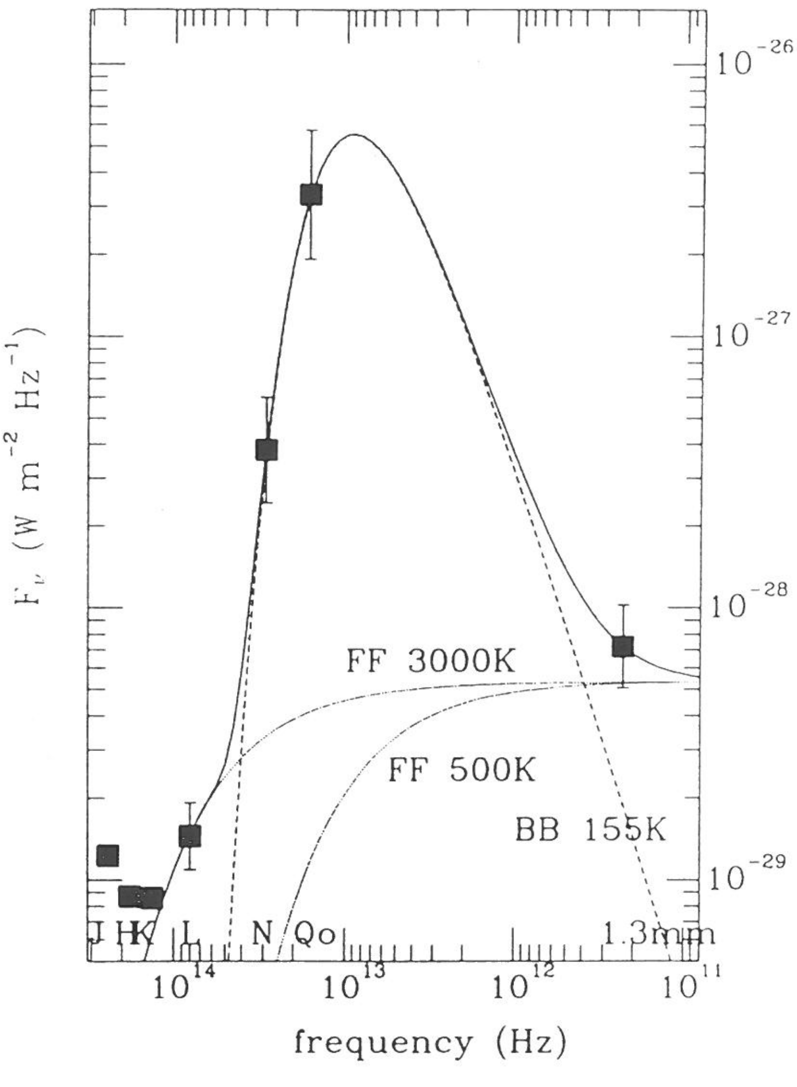


Fig. 14. The "oir" and SEST broadband photometry for days 1316. The points have been fitted by both a black body curve and a free–free radiation.

Galactic Centre Molecular Clouds

(A. Winnberg)

Observations obtained during the early 70s demonstrated that molecular clouds dominate the interstellar medium in the inner 500 pc of the Galaxy and that the density of molecular clouds is far higher in this region than in any other part of the Galaxy. Although it is less than 0.2% of the galactic disk by volume, nearly 10% of the galactic mass is found there.

The common isotopic species of carbon monoxide, $^{12}C^{16}O$ (hereafter called ^{12}CO), is the most often used tracer of molecular gas. Comparisons of ^{12}CO spectra with spectra of the rarer ^{13}CO or the much rarer $^{12}C^{18}O$ (hereafter called $C^{18}O$) species demonstrate that the ^{12}CO J=1-0 line is highly saturated, having optical depths of several hundred in some directions toward the galactic centre region. The various isotopic forms of the CO molecule are excited into emission in regions having molecular hydrogen densities $n(H_2) > 200$ cm^{-3}. Most of the gas in the galactic centre has much higher densities than this and can be detected in molecules of high dipole moments such as NH_3, H_2CO, and CS. Because the ^{12}CO line is so saturated, it is not a good tracer of the cloud distribution, or of the column density along the line of sight. It may, for example, be self-reversed and show a local minimum in brightness toward regions of high column density. Therefore, it is necessary to observe the molecular gas in less opaque lines to measure accurately the distribution of the column density and the kinematics of this gas. ^{13}CO creates much less opaque line radiation due to the high ratio $[^{12}C]/[^{13}C]$ (20 - 40). However, the optical depth in the ^{13}CO J=1-0 line sometimes exceeds unity in the galactic centre clouds. Therefore, observations of $C^{18}O$ yield the most reliable results for gas distribution and kinematics since the ratio $[^{16}O]/[^{18}O]$ is of the order of 175 - 400.

The SEST is currently being used in a large-scale survey of the area around the galactic centre in the J=1-0 and 2-1 lines of $C^{18}O$. So far the area has been observed in the J=1-0 line and a first paper is in preparation. Only 123 MHz from the J=1-0 $C^{18}O$ line there is a line of isocyanic acid (HNCO; $J_{KK'}=5_{05}$-4_{04}). Therefore these two lines have been observed simultaneously in the same band. The great advantage of the HNCO molecule is that its rotational excitation is dominated by the IR radiation field for low and intermediate densities. This enables us to pinpoint regions of enhanced IR radiation which can be compared with direct IR observations. As an example of the data, fig. 15 shows (a) the 20-cm continuum map of Yusaf-Zadeh (contours) and the positions observed with SEST (crosses), (b) the J=1-0 $C^{18}O$ emission integrated in velocity from 15 to 20 km s^{-1} (relative to LSR), and (c) the $J_{KK'}=5_{05}$-4_{04} HNCO emission integrated over the same velocity interval. The coordinate axes are galactic longitude (horizontal) and latitude (vertical), and the scales are marked in minutes of arc. Note the higher contrast of the HNCO map as compared to the $C^{18}O$ map.

This project addresses such topics as morphological relationships, gas dynamics and interactions between magnetic fields and molecular clouds and the origin of the ionization. Evidence for non-gravitationally driven gas will be looked for. Such non-gravitational forces could be stellar winds or they could emanate from magnetic fields that possibly reach milligauss strength along the "Arc". The survey could yield indications of varying

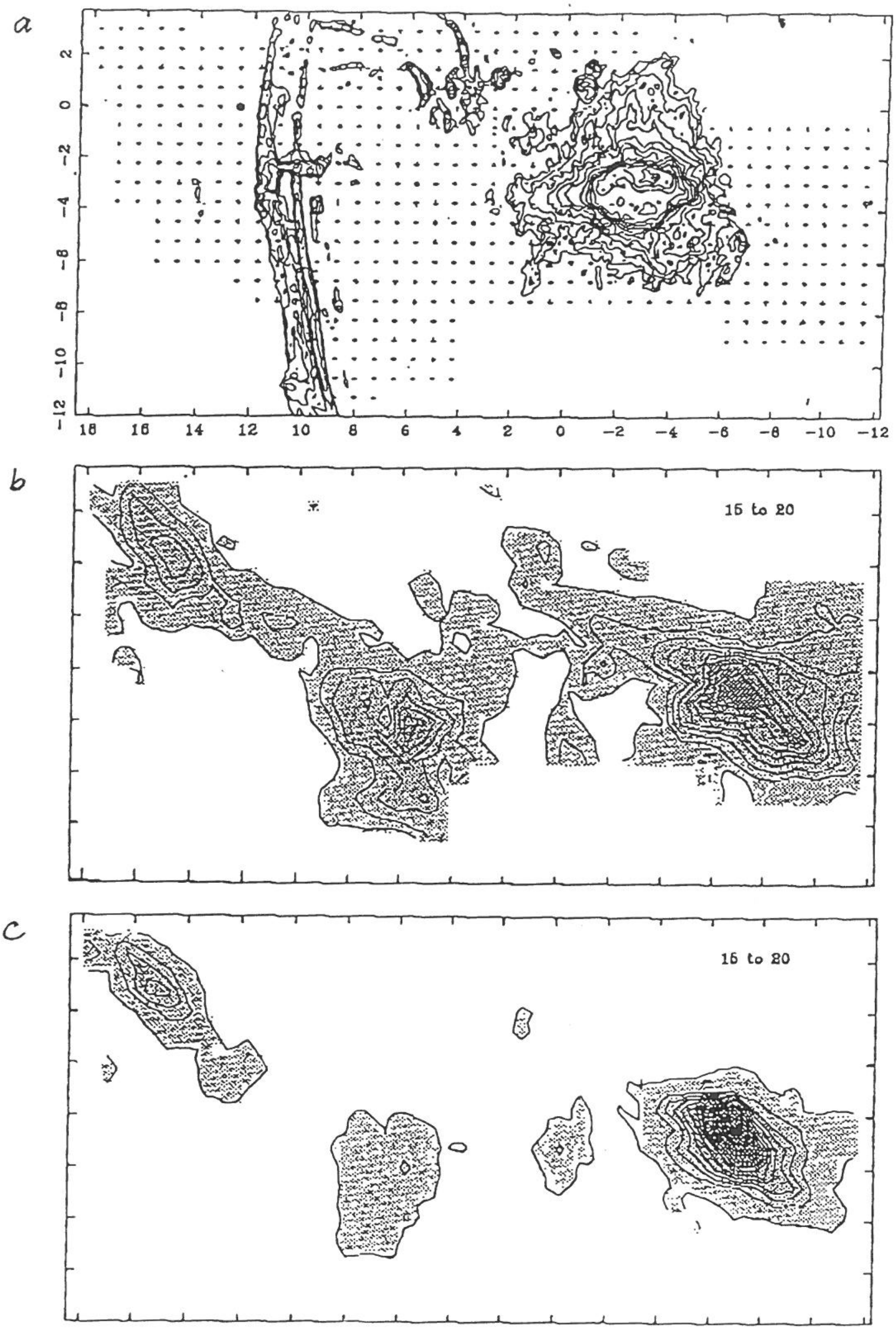


Fig. 15. (a) the 20-cm continuum map of Yusef-Zadeh (contours) and the positions observed with SEST (crosses), (b) the J=1-0 $C^{18}O$ emission integrated in velocity from 15 to 20 km s^{-1} (relative to LSR), and (c) the $J_{KK'}=5_{05}-4_{04}$ HNCO emission integrated over the same velocity interval. The coordinate axes are galactic longitude (horizontally) and latitude (vertically) and the scales are marked in minutes of arc.

temperature from cloud to cloud from the ratio between the J=1- 0 and J=2-1 $C^{18}O$ line intensities. This is a very important goal of the project because there is evidence that the interstellar dust is colder than the gas in the centre region. Therefore the question of the excitation mechanism of the CO molecules is of considerable interest. There is another interesting heating mechanism. Due to the huge potential well in the galactic centre there could be tidal forces that disrupt the molecular clouds, leading to turbulent shocks which heat the medium. There is observational evidence that the +20 km s^{-1} cloud is debris of a tidal disruption which is falling towards the galactic centre, dissipating gravitational energy and therefore heating the medium.

Another important aspect of this project is to determine the geometrical relationships between the galactic centre continuum sources - such as the nonthermal Arc and Sgr A East, the thermal arched filaments and Sgr A West, and the molecular regions. The largest molecular clouds near the Sgr A Complex are the so-called +20 and +50 km s^{-1} clouds which appear to be condensations in a continuous molecular belt lying more or less parallel to the galactic plane. The outer edges of the radio continuum shell Sgr A East fit well against the edges of the +20 and +50 km s^{-1} clouds, suggesting physical contact and interaction between the continuum and molecular components of the complex. One important question is whether these molecular clouds can be considered to be reservoirs feeding molecular gas into the circumnuclear disk which is rotating about Sgr A West with velocities of the order of 100 km s^{-1}.

Giant Molecular Clouds and Interstellar Chemistry
(A. Hjalmarson).

Except for the possible black hole in the Galactic Centre molecular clouds are the most massive gravitationally bound objects in the Galaxy. Although the volume filling factor of these clouds is only 1%, the total H_2 mass ($3 \times 10^9 M_\odot$) is as large as the HI mass. Most of the H2 mass is collected in giant molecular clouds of masses larger than $10^5 M_\odot$. The molecular clouds constitute the active, star forming component of the interstellar medium. Molecules can form and survive in the interiors of these clouds which are protected from ionizing UV light by the efficient dust absorption.

Molecular lines allow us to study the physical and chemical conditions deep inside these otherwise dark nebulae. Such cloud probing studies are important for our knowledge of the initial conditions for star formation and also to find signatures and influences of star formation in the parent clouds. Studies of the rather complex interstellar chemistry are not only interesting for their own sake but also have a strong bearing on the cloud evolution because of the efficient cooling provided by the molecular lines. To understand the cooling we need to know molecular abundances as a function of physical conditions.

A number of rather detailed observations of molecular clouds have been performed by SEST, highlighting the smooth and efficient operation of this telescope. The dedicated studies of the Chamaeleon dark clouds by Mattila and his collaborators deserve special mention here. These and other observations have also demonstrated that the southern hemisphere contains molecular outflow sources very well suited for detailed observations aiming at an understanding of the outflow process as a sign of very early stellar evolution and of the interaction of the outflow with the surrounding parent cloud. Here the high quality optical observations of associated jets and flows by the ESO optical telescopes are very important.

A useful illustration of how careful analysis of high quality SEST data can lead to unique conclusions about cloud physics and chemistry has been provided by Bergman. High S/N observations of CH_3CN, $CH_3{}^{13}CN$, ${}^{13}CH_3CN$ J=6-5 and 13-12 (figure 16) transitions toward the southern molecular cloud core G327.3-0.6, complemented by CH_3C_2H data, were analysed by five different multi-level methods. Two nearby cloud cores were shown to exist, a cold one (T_k = 30 K) and a hot one (T_k = 150 K), each containing $10^3 M_{\odot}$. In the hot core large gradients in temperature ($T_k = 40 - 200$ K), density ($10^6 - 10^8$ cm^{-3}) and CH_3CN abundance ($10^{-10} - 10^{-7}$ with respect to H_2) were for the first time convincingly shown to exist in an interstellar cloud. Very small scale clumping and very large velocity gradients are present in the hot core which is probably associated with an ultracompact HII region caused by a newly formed massive star.

Another example of the good data quality and excellent baselines delivered by SEST can be found in the 220 -260 GHz spectral scan of three nearby positions in the massive molecular cloud Sgr B2. Composite spectra for the two cloud cores (M) and (N) are shown in figure 17. Our ultimate goal here is to understand how the chemistry varies with the physical conditions. The ongoing analysis of the data clearly demonstrates that we are near (and sometimes beyond) the "confusion limit" and also tells us about the high reliability of the data. Even very weak features in the spectra appear to be real. This has been verified by repeated observations with different overlapping frequency bands and can also be judged from the co-existence of such features in spectra for the two chemically and physically diffrent cores (M) and (N) (see figure 18). This is very promising for the analysis (although also very time consuming !) since it allows comparative multi-transition studies also in cases where the molecular abundances are very different. From multi-transition analysis we find that the dominant SO_2 emission emanates from the (M) source, which may be an outflow region. In contrast the emissions from CH_3OH, $(CH_3)_2O$, and $HCOOCH_3$ as well as CH_3CN, C_2H_3CN and C_2H_5CN are strongly peaked in the warmer, denser and more massive core (N). The spectral scan data will not only provide accurate information about molecular abundances; the population distributions (rotation diagrams) of the various molecules also tell us about excitation conditions. To fully benefit from this information about source structure we are also mapping the temperature, density and velocity structure of the Sgr B2 core region using CH_3CN, CH_3C_2H and CS as probes. Our future goal is to combine our 220-260 GHz spectral scan with an ongoing 30-115 GHz line survey of our Sgr B2 source positions at the 45 m telescope of Nobeyama Radio Observatory. In this way also lower excitation regions will be probed and a better understanding of the core-envelope structure can be achieved.
Since SEST is a unique millimetre wave facility in the southern hemisphere it has a very important role as a "groundbased support instrument" for space borne astronomy. Such preparatory studies of molecular clouds are already ongoing in support of ISO programs. Scientists involved in the forthcoming submillimetre wave satellites ODIN (Sweden-Canada-France-Finland) and SWAS (USA) have agreed on creating a common "molecular cloud data base", which is necessary for the planning of the observing

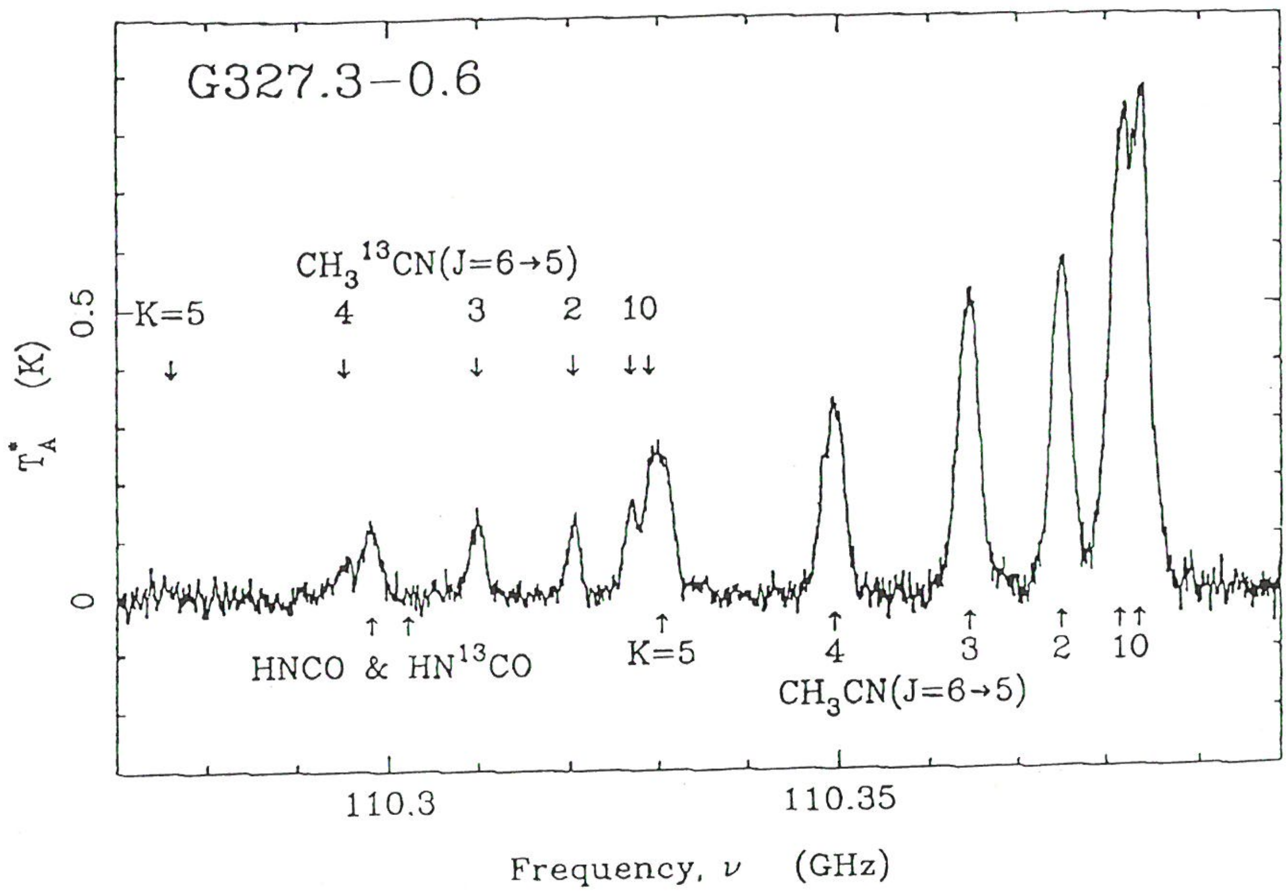


Figure 16. Spectrum showing the J = 6-5 transitions of CH_3CN and $CH_3{}^{13}CN$ toward the hot core in G327.3-0.6

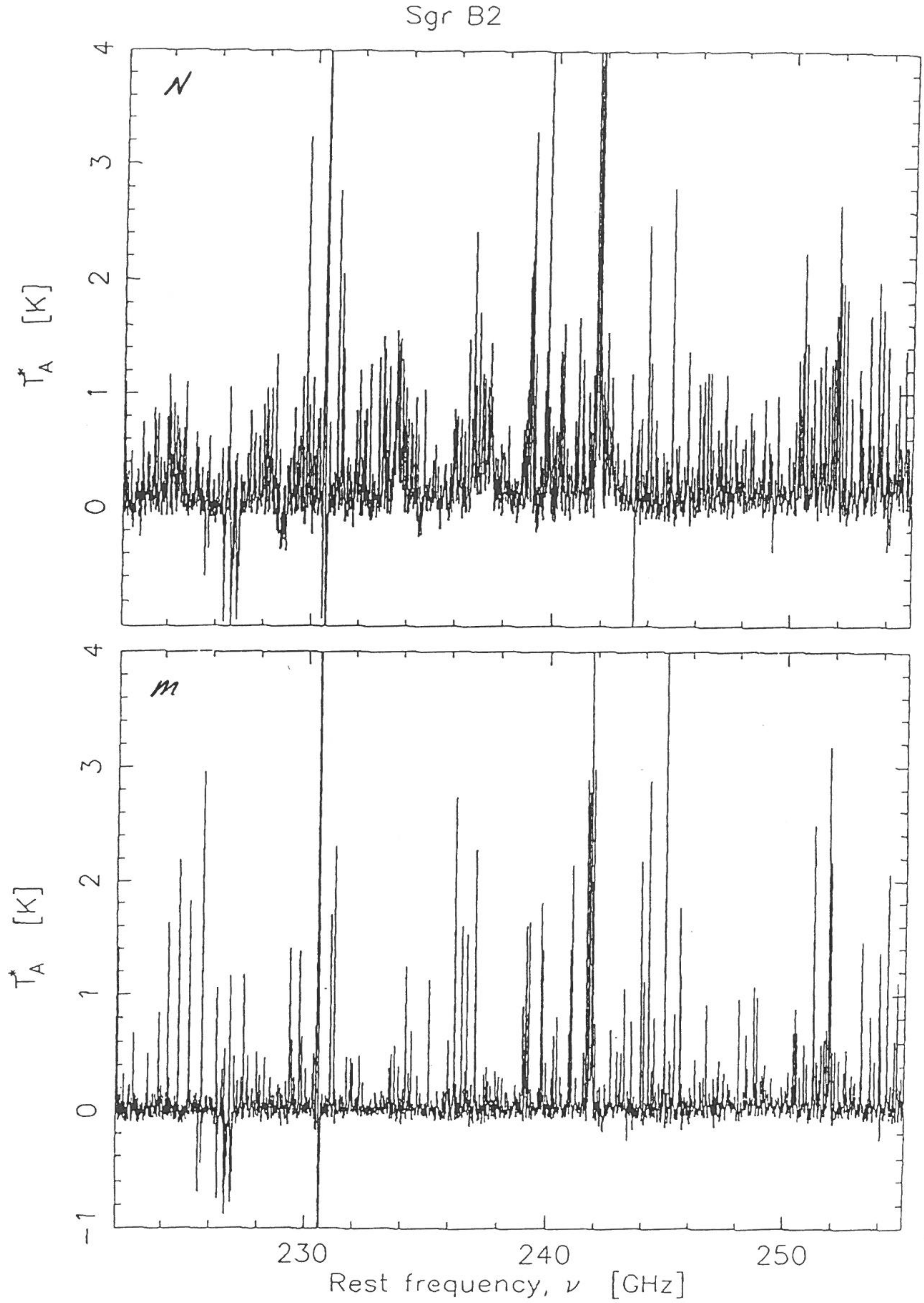


Figure 17. Overview spectra toward Sgr B2 (M) and (N) illustrating the present frequency coverage. The line density in the N position is twice as high as in the M position.

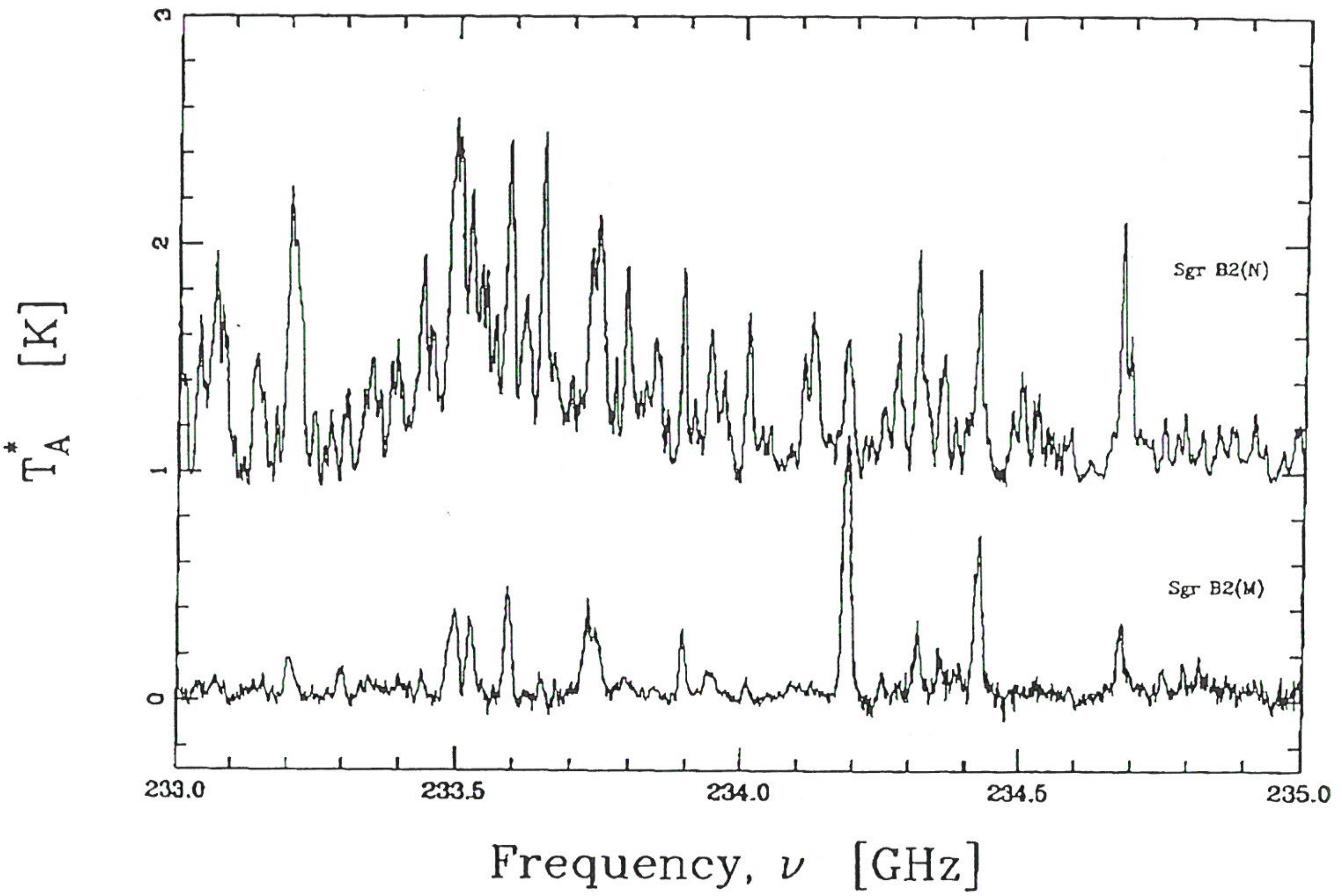


Figure 18. Full resolution spectra illustrating the co-existence of many line features in the Sgr B2 (M) and (N) cores.

programs as well as for the interpretation of the satellite data. For the southern sky such data are to a large extent lacking and the first "desperately needed" ODIN/SWAS support observing program is scheduled on SEST for April 1994. Extensive follow up studies stimulated by SWAS and ODIN discoveries may be expected. Likewise SEST is a "must" for pre- and post- FIRST observation of molecular clouds/star forming regions.

SEST Observations of Molecular Clouds and Star Forming Regions
(K. Mattila et al.)

Four out of about six of the nearest rich low-mass star formation regions within 200 pc are accessible only from the southern hemisphere: Chamaeleon I and II, R Coronae Australis, and Lupus. The importance of the southern skies for (sub)millimeter wave spectroscopy has also been strongly emphasized by the space telescopes, especially ISO and ROSAT and also the forthcoming FIRST of ESA and Odin of Sweden. Preparatory and complimentary studies with SEST are essential. In the initial 5-yr phase the SEST has been used mainly for the basic surveys and inventory of the southern skies. From now on the emphasis will be shifted more towards detailed physical studies of the identified objects, utilizing especially the SEST (sub)millimetre capabilities.

The Chamaeleon I molecular cloud has been an important object for SEST studies. With some 80 low and intermediate mass newly-born stars at a distance of only 140 pc it is an excellent laboratory for studies of the star formation - molecular gas connections. The whole cloud has been mapped in the 3 mm $C^{18}O$ transition, showing that the dense cores are mostly - but not always - connected to present star formation activity centers. Some of the dense cores in Cha I have been investigated in greater detail with SEST using spectral lines in the 3 mm and 1.3 mm windows. In ^{12}CO surveys several outflow sources have been discovered and mapped in ChaI. Two especially strong ones, associated with the star formation centers near Ced112 in the North and Ced 110 near the center of ChaI, have been investigated in detail in several molecular lines.

To study the specific conditions required in the parental dense gas cloud which give rise to star formation the Cha III cloud has also been observed; it appears to be totally devoid of star formation. Another similar project is the detailed study of two Bok globules in the Cha region. One of them, the so called Thumbprint Nebula, is devoid of newly-born stars while the other globule near Cha II, which in its outer appearance is very similar to the former, has given birth to at least one star. The dense gas distributions as observed by SEST are clearly different for these two globules. Most of these regions will be further studied in the framework of the ISO guaranteed time program by both the ISOPHOT and CAM teams.

The R CrA molecular cloud is another very nearby ($r \sim 130$ pc) active star formation region. SEST mapping of this cloud in the 3mm $C^{18}O$ line has revealed a system of dense cores with considerable substructure and, most remarkably, an indication of what appears to be a large rotating "interstellar disk" associated with the most active star formation center in R CrA, the "Coronet cluster" of infrared stars. The molecular outflow associated with this disk is currently being studied with SEST with high spatial resolution.

Other targets for SEST studies have been the cometary globules associated with the Gum Nebula. The Gum Nebula offers a unique Southern Sky laboratory to study the influences of large scale stellar winds etc. on low mass star formation.

For the rare but important case of star formation at large distances from the galactic plane there are some excellent objects in the south, such as NGC 5367. For studies of high mass star formation regions the southern skies offer excellent opportunities: the whole inner spiral arms of the Galaxy are accessible for (sub)millimetre molecular line studies only with SEST. It is important to investigate the dependence on galactocentric distance of the dense molecular cores which give birth to massive stars. A CS-multitransition study is aimed at determining the fundamental physical parameters of some 150 southern high-mass star forming regions, signposted by interstellar H_2O masers. This study fully exploits the SEST submillimetre capabilities and substantially complements the northern restricted object list throughout the southern sky.

As the only southern-hemisphere millimetre and submillimetre telescope SEST has a unique mission to fullfil for several years to come.

Molecular Clouds, Dust Clouds, and Cometary Globules
(T. Wilson et al.)

The structure, content and evolution of molecular clouds is crucial to our understanding of the star formation process. Stars are born deep inside molecular clouds, hidden from view in the optical. After their formation, these stars interact with the molecular clouds by means of outflows, and in still later phases, eject material which has been processed during stellar evolution. Studies of molecular clouds with SEST have concentrated on the determinations of isotopic content, cloud masses, densities and kinetic temperatures, and the effect of environment on cloud properties.

In the field of isotope ratios, a long integration in the J=1-0 line of CO and ^{13}CO has been made toward the star Zeta Ophiuchus. The star is behind a molecular cloud which has about 1 to 2 magnitudes extinction. A 24 hour integration gave a ($^{12}CO/^{13}CO$) ratio of > 55; this is a realistic value since the J=1-0 line of ^{12}CO is optically thin (Wilson *et al.* 1992). Follow up work was done by Sheffer *et al.* (1992), using CO absorption lines in the UV, taken with the Hubble Space Telescope. The CO absorption line data give a ratio of 127. Thus, the radio and optical results are consistent.

Integrations of between 5 and 12 hours have been made toward a number of molecular maxima, in the J=1-0 lines of $H^{13}C^{14}N$ and $H^{12}C^{15}N$, to determine the ($^{14}N/^{15}N$) ratios in the galaxy as a function of distance from the galactic center. For these results, all lines are optically thin, from least squares fits to the hyperfine components of $H^{13}C^{14}N$. A plot of the results is shown in Fig. 19. Additional measurements of this ratio for 4 sources in the galactic center have been made. In the center, this ratio is about 300, but if the optical depths of $H^{13}C^{14}N$ are large, the ratio will be increased.

For sources outside the galactic center, the J=2-1 line of $C^{18}O$ has been mapped toward

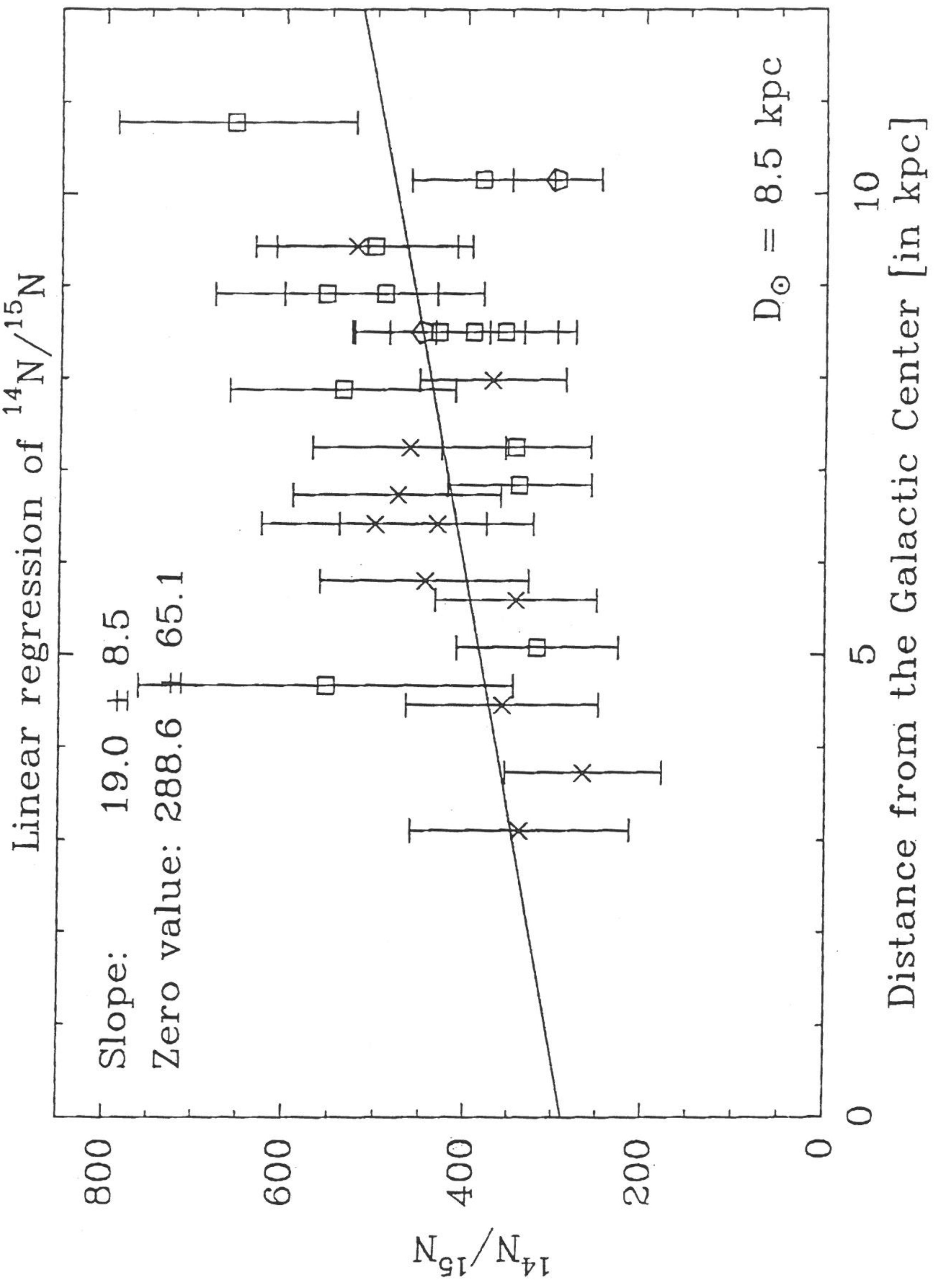

Linear regression of $^{14}N/^{15}N$
Slope: 19.0 ± 8.5
Zero value: 288.6 ± 65.1
$D_{\odot}$ = 8.5 kpc
Distance from the Galactic Center [in kpc]
$^{14}N/^{15}N$
0
5
10
0
200
400
600
800

Figure 20

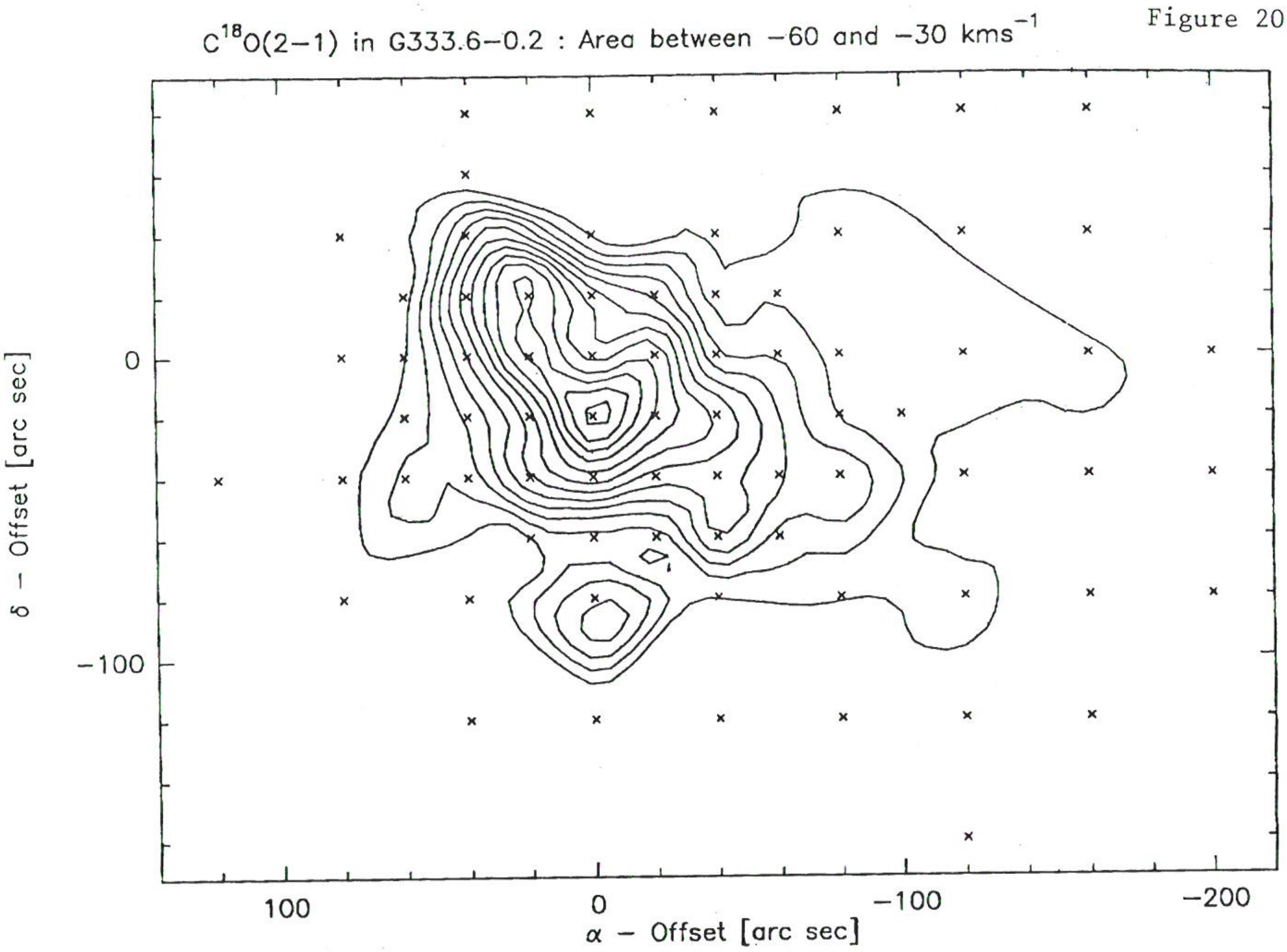
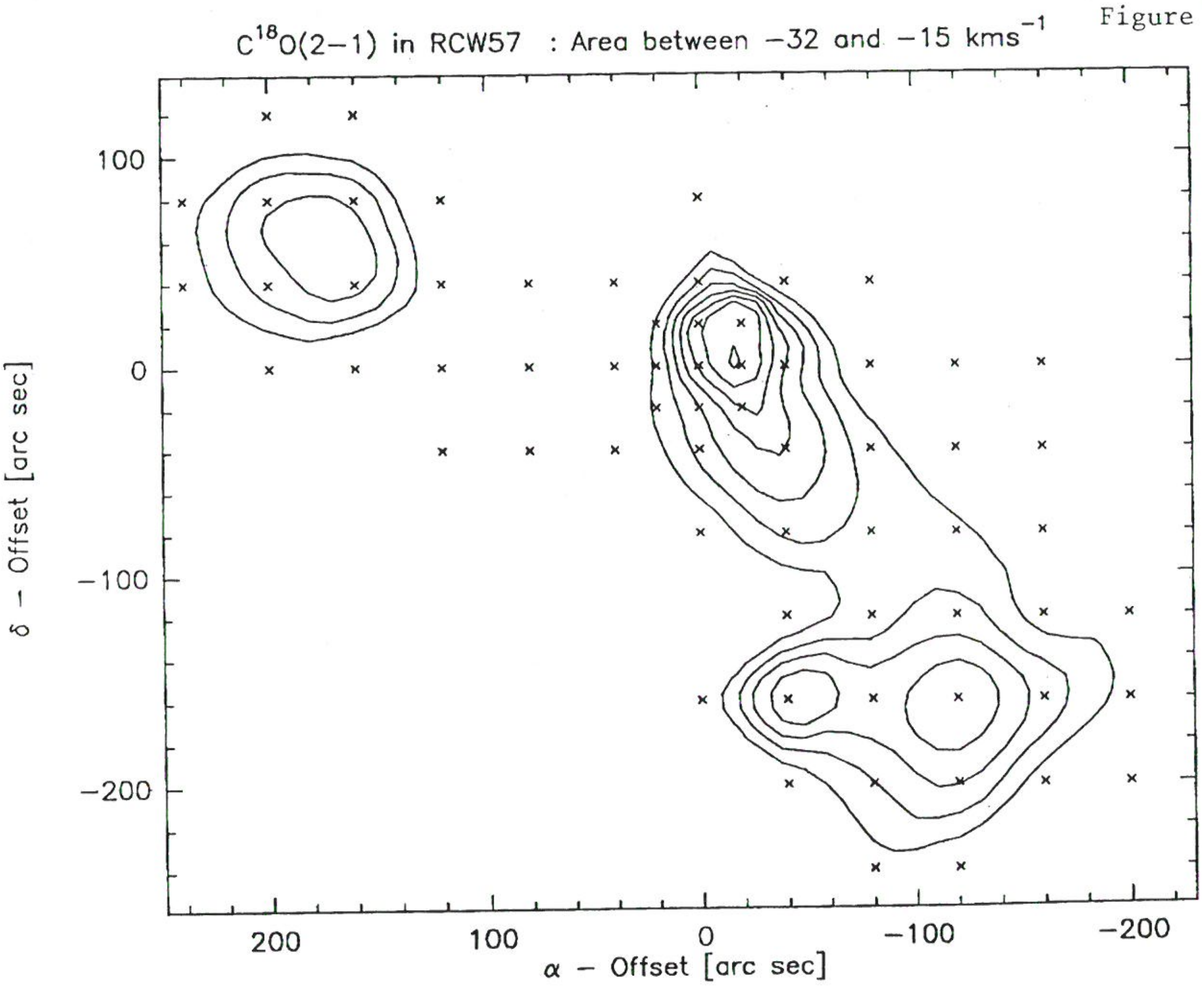


Figure 21



warm molecular clouds where O and B stars have formed. The SEST results will be compared to bolometer measurements also made with SEST, and near IR data taken with the ESO 2.2 meter telescope. The goal is to compare dust and molecular abundances in sources. Two contour plots of the $C^{18}O$ J=2-1 line data are shown in Figs. 20 and 21. It appears that the $C^{18}O$ data show less contrast than the dust data, that the maxima are in somewhat different positions, and that the column densities obtained from $C^{18}O$ are factors of a few lower than those obtained from dust.

There are also extensive maps of compact dust clouds catalogued by Clemens and Barvanis (1988), in the J=2-1 and J=1-0 lines of $C^{18}O$ (Lemme, 1994). These clouds are thought to be rather quiescent regions where low mass star formation may be occuring. The SEST results will be compared to ammonia inversion line data and to near IR maps.

The first CO line map of a cometary globule, CG1, was made by Harju et al. (1990). Cometary Globules are embedded in enhanced radiation fields, here the Gum nebula. Their properties seem to be determined by these surroundings: based on the SEST data, the CG's are shocked, non-virially stable regions of moderate density and column density, which are warmer than dark clouds, and which may contain a few stars. Molecular clouds in the galactic center region are of great interest for two reasons. First, the results show us the response of such objects under high tidal forces, high radiation fields and magnetic forces, and second, these allow a direct comparison with maps of the centers of external galaxies. With SEST, a detailed study of 2'by 2' regions in 36 galactic center molecular clouds has been made in the J=1- 0 and 2-1 lines of $C^{18}O$, and the J=2-1 and 5-4 lines of CS, and the J=2-1 line of $C^{34}S$ (Hüttemeister 1993). These data allow a determination of H_2 density and mass. The ratios of the J=2-1 to J=1-0 lines of $C^{18}O$ are well below the optically thin thermalized valve of 4. Thus, one can use the line ratios to determine H_2 densities as well as column densities. From $C^{18}O$, the local H_2 density is between 2 and 4 $10^4 cm^{-3}$, and the column density of H_2 is between 5 $10^{21} cm^{-2}$ and $10^{23} cm^{-2}$. These are the first realistic values obtained for the galactic center clouds. The densities are somewhat lower than the values obtained from the Bell Labs surveys, based on only the J=1-0 line of ^{13}CO and J=2-1 line of CS (Bally *et al.* 1988). The CS data from SEST give a factor of 10 larger density than that from $C^{18}O$. Presumably, the CS refers to only the densest regions, embedded in more extended lower density envelopes.

Recently, there have been observations of CO absorption toward background quasars. These results have been interpreted as showing that large amounts of cold molecular gas is present in the outer parts of the Galaxy. This is an exciting new development which may link molecular line astronomy to galactic dynamics, baryonic missing mass, recent star formation in elliptical galaxies and cooling flows in clusters of galaxies. Additional evidence is needed to better establish this connection, and SEST is an ideal instrument for extending CO absorption line observations to the southern sky to test this hypothesis.

Bally J., Stark A.A., Wilson R.W., Henkel C. 1988 ApJ 324, 223
Clemens D., Barvainis R. 1988 ApJ Suppl 68, 257
Harju J., Sahu M., Henkel C., Wilson T.L., Sahu K., Pottasch S. 1990 A&A 233, 197
Hüttemeister S. 1993 Ph.D. Thesis, Bonn Univ.
Lemme C. 1994 Ph.D. Thesis, Bonn Univ., in prep.

Sheffer Y, Federman S.R., Lambert D.L., Cardelli J.A. 1992 ApJ 397, 82
Wilson T.L., Mauersberger R., Langer W.D., Glassgold A.E., Wilson R.W. 1992 A&A 262, 248

Star Formation and Young Stars

(B. Reipurth)

The availability of the SEST bolometer has for the first time allowed the study of cold dust in southern star forming regions. A survey has been made of Herbig–Haro energy sources at 1300 micron, detecting 53 out of 59 objects. These extremely young objects turned out to be surrounded by considerable amounts of dust, suggesting circumstellar gas masses in the range from a few tenths to several solar masses. One is most likely detecting the vestiges of the collapsing envelopes from which the stars were born (Reipurth et al. AA 273, 221, 1993).

While Herbig-Haro energy sources are still relatively evolved, and therefore have enough warm dust to be detected by IRAS, true protostars should be so cold (< 20 K) that they would principally be emitting at (sub)mm wavelengths. To find such objects, several groups have used the SEST and bolometer to scan star forming regions, using various search criteria. A search of the surroundings of the youngest stars known has been surprisingly successful, and almost a dozen protostellar candidates, not detected by IRAS, have been identified so far.

The SEST has been used extensively to study molecular outflows in southern star forming regions. A recent question of particular concern is how molecular flows and Herbig-Haro flows are related to each other. It seems likely that as Herbig-Haro jets intermittently ram through their ambient medium they impart momentum to their surroundings, thus producing the molecular outflows. To test such hypotheses SEST has been employed to search for molecular outflows around prominent southern Herbig-Haro jets, and molecular outflows were found associated with HH 111, HH 46/47 and HH 56/57. Detailed ^{12}CO maps of these flows have allowed a closer examination of the proposed relation between the optical and radio outflow phenomena.

Study of Translucent Clouds with Combined SEST and CAT Observations

(R. Gredel)

The study of translucent molecular clouds has recently become possible due to the development of sensitive detectors both for optical absorption line observations and for millimeter emission line measurements. Optical and millimeter observations complement each other in various aspects: the angular resolution of optical absorption line measurements, about 0.04AU at 200pc distance, is not reached in the millimeter region, where single dish data have typically 10^4AU resolution (45″ beam). On the other hand, a velocity resolution of 0.1 km s^{-1} is routinely achieved in the millimeter region, which is enough to resolve the line profiles. Absorption line studies provide accurate column densities in the line of sight towards the background star, but maps obtained in millimeter emission lines can be used to obtain information about the kinematics and the structure of the whole cloud. The foreground H_2 column densities can be determined from the reddening of the background stars or from an empirical relation between CH and H_2. In addition, valuable probes of physical conditions, such as C_2, have no mm spectrum and can only be detected in the visible. Extinction and polarization measurements provide information on the dust in the cloud.

A sample of southern translucent clouds has been studied with the SEST and the CAT in an effort to determine the physical and chemical conditions in the clouds. The optical observations have resulted in accurate column densities of CH, CH^+, CN, and C_2 towards background stars, have allowed determination of the kinetic temperature, density and electron fraction of the foreground material, and have provided constraints on the kinematics through determinations of the Doppler parameter along the lines of sight. The millimeter observations have provided information on the extent, structure, mass and kinematics of the clouds, and the influence of photoprocesses on the chemistry of the clouds (Gredel et al. 1991, 1992, 1993, 1994; van Dishoeck et al. 1991).

The translucent clouds studied with SEST show evidence of spatial structure on all scales, down to the resolution of the telescope. The true origin of the small-scale structure is not yet understood. A comprehensive study of the cloud in front of HD 210121 has shown that the gas density is rather constant across the cloud, despite the rich structure seen in the CO map. This is because the cloud occupies a parameter space where small variations in physical parameters result in large variations of the observable CO intensity. In other translucent clouds, the densities inferred from multi-line CO studies are up to one order of magnitude higher than those found from a C_2 analysis. This indicates small scale clumping, or gas density variations.

Fractional abundances of various molecules were determined and compared with the predictions of chemical models. Diatomic molecules such as CN and C_2 are quite abundant, and can be well modelled if the physical parameters inferred from the optical observations are used. Polyatomic species such as C_2H and C_3H_2 are not detected, and HCN and HCO^+ appear rather abundant, in contrast to model predictions. More detailed modelling, with a more realistic description of the physical structure of the clouds, is underway to properly interpret these observations.

Studies of the enigmatic CH^+ ion, previously only observed in diffuse clouds, do not support a single-shock origin for the formation of the ion. The widths and intensities of wings seen in the CO profiles were used to estimate contributions from hot molecule formation scenarios in warm turbulent boundary layers. The estimated amount of CH^+ produced by turbulent chemistry fails by about one order of magnitude to account for the average abundance. Observations pertaining to these issues are continuing.

Gredel, R., van Dishoeck, E.F., Black, J.H., 1991, A&A 251, 625
van Dishoeck, E.F., Black, J.H., Phillips, T.G., Gredel, R. 1991, ApJ 366, 141
Gredel, R., van Dishoeck, E.F., de Vries, C.P., Black, J.H., 1992, A&A 257, 245
Gredel, R., van Dishoeck, E.F., Black, J.H., 1993, A&A 269, 477
Gredel, R., van Dishoeck, E.F., Black, J.H. 1994, A&A *accepted 11/93*

Evolved Stars

(L.-A. Nyman)

Evolved stars undergoing mass loss are objects that are well studied in the (sub)mm region. They are mostly pulsating stars on the Asymptotic Giant Branch (AGB) consisting of a degenerate C–O core with Hydrogen and Helium burning in layers around the core, but also objects in even later stages of their evolution such as Proto Planetary and Planetary Nebulae (PPN and PN). There are still many questions to be answered about the evolution of stars on the AGB. The mass loss mechanism is still unknown, and very little is known about the details of the transition from an AGB star to a PNe. Studies of AGB stars are important for our understanding of the chemical evolution of our Galaxy, since they are the most important contributors of enriched material to the interstellar medium.

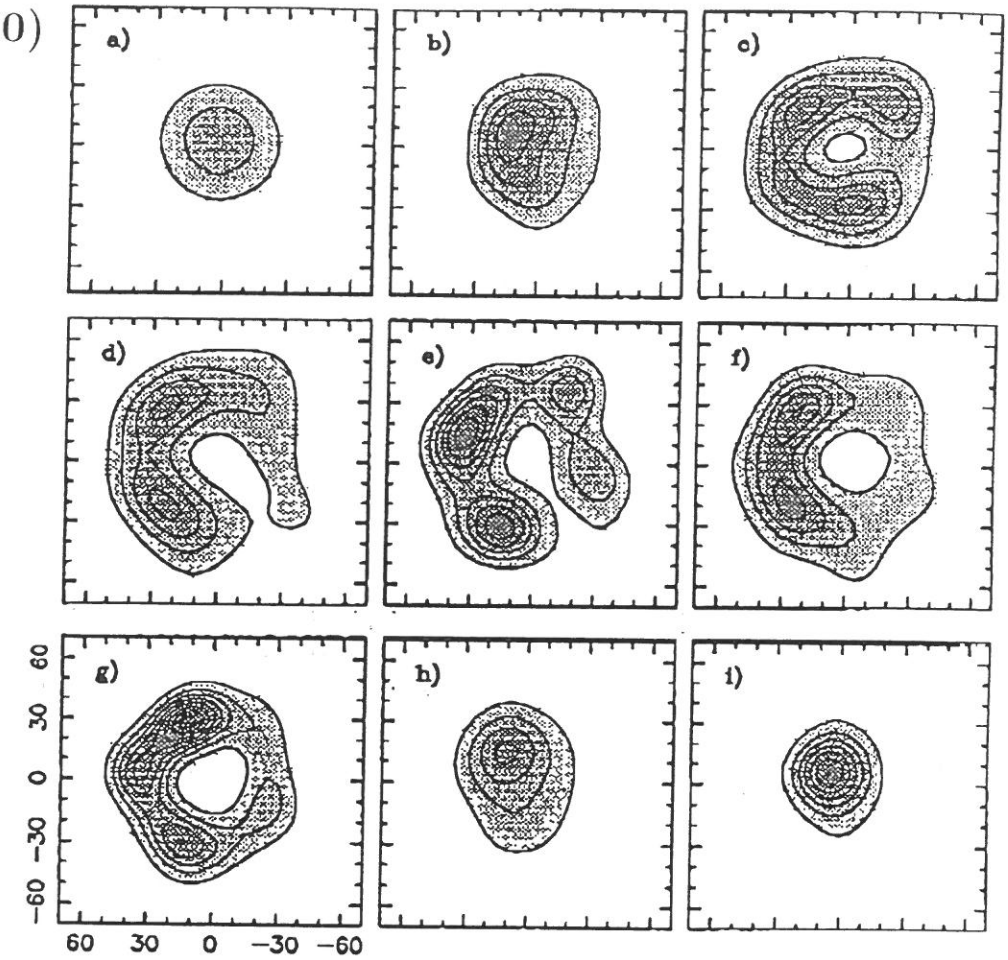
In many evolved stars the mass loss rate is so high that they are completely obscured optically, and they can only be studied at infrared and (sub)mm wavelengths. (Sub)mm observations of spectral lines of various molecules in their circumstellar envelopes (CSE's) make it possible to study dynamics and kinematics, and to determine mass loss rates, outflow velocities, and chemical composition. Various molecules sample different parts of the CSE, *e.g.* SiO masers, are situated near the surface of the star (within 10^{13} cm), while CO emission traces the envelope out to more than 10^{18} cm. The emission from the dust can be studied through bolometer observations and the dust mass can be determined since the emission is optically thin at mm wavelengths.

The SEST has been used to study essentially all aspects of stars undergoing mass loss, and has made important contributions to the field. Since it is a unique instrument in the Southern Hemisphere it has been used for various surveys of southern samples obtained from IRAS and near infrared data, e.g. surveys of CO and SiO maser emission from IRAS sources (the SEST has discovered more than 100 new SiO masers towards evolved stars, *i.e.* about 30% of all those now known) (Nyman *et al.*, 1992, 1993b; Haikala, 1990) and surveys of various molecular lines in infrared bright carbon stars (Olofsson *et al.*, 1993a, 1993b), resulting in many new detections and improved statistics on the properties of the CSE's around various types of evolved stars. One of the highlights has been the detection of detached circumstellar shells by Olofsson *et al.* (1992). These are stars surrounded by a shell from a brief period of intense mass loss, possibly caused by a "thermal pulse" (a short, explosive burning of the He layer). This may be an important way to isolate the so far unknown mechanism behind the high mass loss rates on the AGB. The most extended shell was first detected at SEST (fig. 22) and the telescope has also been used to study the less extended ones using the high spatial resolution at 345 GHz of the CO(3–2) line (Fig. 23).

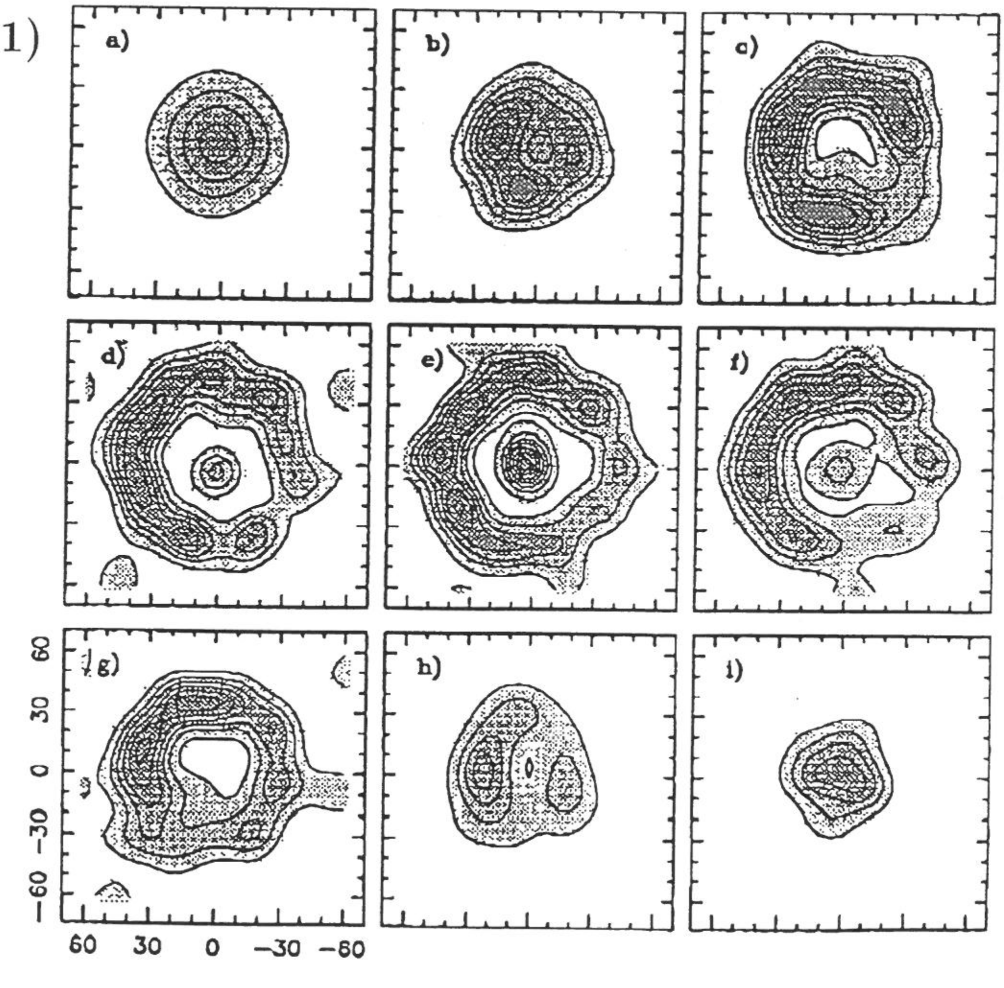
The SEST has been used to study molecular abundances in oxygen and carbon rich CSE's. A spectral line survey of the carbon star IRAS 15194-5115 showed molecular abundances similar to IRC+10216 (a well studied carbon star in the northern sky) except that the ^{13}C isotopomers were significantly more abundant in IRAS 15194-5115 (Nyman *et al.*, 1993a). In oxygen rich CSE's all the carbon is expected to be locked up in CO. However, HCN has

Figure 22

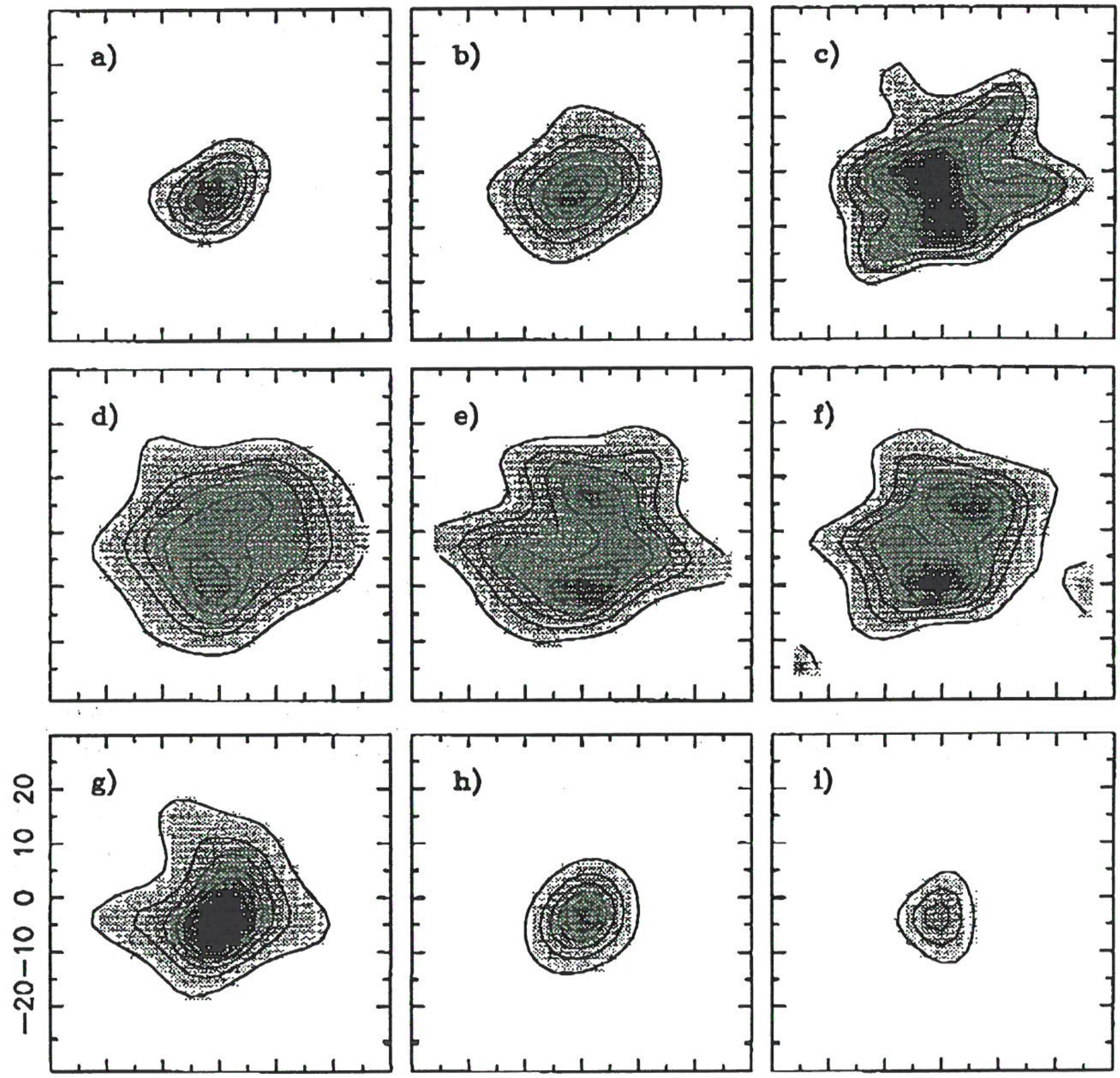
CO(1-0)



CO(2-1)



R Scl CO(J=3-2)



been detected in several O-rich envelopes with SEST, and H_2CO was detected for the first time in such envelopes (Lindqvist *et al.,* 1992). It is not clear why these carbon-bearing species exist in O-rich envelopes; one reason may be that methane is more abundant than previously thought, injecting carbon into the envelope through its photodissociation.

During the PPNe stage often a brief period of high mass loss occur, sometimes at high velocities in a bipolar outflow. Some of these objects may be binary stars and the outflow channeled by an accretion disc. Very little is known about PPNe since the stars pass through this evolutionary stage very quickly, and at a given time there are very few of these objects. It is therefore important to discover as many as possible in order to study this evolutionary stage. Surveys of CO emission from various samples of southern PPNe have been done with the SEST by Loup *et al.* (1990), Bujarrabal and Bachiller (1991), and van der Veen der Veen *et al.* (1993). Many interesting objects were discovered, among them HD101584, for which the CO spectrum has one of the largest velocity widths ever observed in such objects (Loup *et al.,* 1990; Trams *et al.,* 1990). Also stars on the AGB sometimes show high velocity wings in their CO spectra, e.g. the S-type star π^1 Gru (Sahai, 1992).

Because of the high UV flux from the central star in PNe most molecules are expected to be photodissociated in the envelope. However, emission from many molecules has been found in PNe. They probably exist in dense clumps of gas that have not yet been photodissociated. Cox *et al.* (1992) detected several molecular species towards two southern PNe pointing to a chemistry dominated by photodissociation and shocks. Through CO observations SEST has been used to study kinematics and properties of several bipolar PNe (Sahai *et al.,* 1990, 1991; Cox *et al.,* 1991) and there is an ongoing project to map the CO emission from the Helix Nebula.

The SEST bolometer is presently used to monitor the 1.3 mm emission from a sample of AGB stars and PPNe, and it has been used to observe a sample of compact PNe. There exist very few observations of continuum emission from evolved stars at these wavelengths, and SEST will make important contributions to these studies.

Many more projects concerning evolved stars than the ones described above have been done or are presently being done with the SEST. Among them are projects concerning mass loss mechanisms for AGB stars, the transition from oxygen to carbon rich chemistry which is believed to take place on the AGB through dredge up of processed material, detached shells around oxygen-rich objects, and various types of observations of symbiotic stars. SEST has played an important role in the field of evolved stars through the detection of detached shells, and has increased our knowledge about various evolutionary stages of stars through the possibility to observe southern samples of objects at (sub)mm wavelengths.

References

Bujarrabal V., Bachiller R., 1991, A&A 242, 247
Cox P., Huggins P.J., Bachiller R., Forveille T., 1991, A&A 250, 533
Cox P., Omont A., Huggins P.J., Bachiller R., Forveille T., 1992, A&A 266, 420

Lindqvist M., Olofsson H., Winnberg A., Nyman L.-Å., 1992, A&A 263, 183
Loup C., Forveille T., Nyman L.-Å., Omont A., 1990, A&A 227, L29
Nyman L.-Å. et al, 1992, A&AS 93, 121
Nyman L.-Å. Olofsson H., Johansson L.E.B., Booth R.S., Carlström U., Wolstencroft R., 1993a, A&A 269, 377
Nyman L.-Å. Hall P.J., Le Bertre T., 1993b, A&A 280, 551
Olofsson H., Carlström U., Eriksson K., Gustafsson B., 1992, A&A 253, L17
Olofsson H., Eriksson K., Gustafsson B., Carlström U., 1993a, ApJS 87, 267
Olofsson H., Eriksson K., Gustafsson B., Carlström U., 1993b, ApJS 87, 305
Sahai R., 1992, A&A 253, L33
Sahai R., Wootten A., Clegg R.E.S., 1990, A&A 234, L1
Sahai R., Wootten A., Schwarz H.E., Clegg R.E.S., 1991, A&A 251, 560
Trams N.R., van der Veen W.E.C.J., Waelkens C., Waters L.B.F.M., Lamers H.J.G.L.M., 1990, A&A 233, 153
van der Veen W.E.C.J.,Trams N.R., Waters L.B.F.M., 1993, A&A 269, 231

The Search for Protoplanetary Disks around Main Sequence Stars

(R. Chini)

The search for planets outside the solar system is one of the great challenges of today's astronomy. Since the discovery of strong 100μm excess around solar type stars, interpreted as due to larger- than-normal dust particles in a circumstellar disk, this field of research has gained major progress by ground-based bolometer observations from the MRT and the SEST. Chini *et al.* (1990) have observed five such stars at 870 and 1300μm and found flux densities of 20 – 50mJy (870μm) and 5 – 10mJy (1300μm) from an area of $\approx$ 10" HPBW. The corresponding 1300μm fluxes in a 24" beam at the SEST were typically a factor of 3 larger.

Fitting these data and the IRAS observations by radiative transfer calculations one finds that about $10^{-8}M_\odot$ of dust are distributed within a disk where the outer radius is 2 – 3 times larger than the inner radius. The total diameter is of order 100AU and seems to be correlated with stellar luminosity in the sense that the disk is larger for brighter stars. Grain temperatures range from 50 to 140K. The spectra can only be fitted with a grain size distribution where the smallest grains have radii of 10 to 100μm. The largest grains have diameters in the mm range and the presence of km-sized bodies cannot be excluded.

The detection by IRAS of a dust cloud around the A0V star Vega was a major step in the search for extrasolar planetary material. Altogether IRAS found a dozen Vega-like sources. Because of the Poynting-Robertson effect, which causes grains to spiral into the star, a deficiency of small (< 1mm) grains is quite likely. Due to this effect particles of radius < 1mm located at a distance of 50AU from a solar type (G2V) star are removed in $4 \cdot 10^9$yr; for a distance of 10AU they will have disappeared in less than $2 \cdot 10^8$yr. Such stars surrounded by only large (> 1mm) grains would not have been detected by IRAS: For $T_{dust} = 40$K and a 1300μm flux of 10mJy the 100μm flux is only 0.2Jy and thus below the detection limit ($\approx$ 1Jy). Confusion of the dust emission with photospheric emission from the star will not arise because the latter is negligible.

It is therefore promising to search in the future for dust clouds around main sequence stars where *most* grains are larger than 1mm. In contrast to Vega–type stars, they would have no or only weak 100μm excess emission, but they could be detected at 1300μm. The discovery of grains with sizes greater than 1mm would point towards the existence of still larger bodies, possibly planets. Large (> 1mm) particles emit like black–bodies even at the observing wavelength of 1300μm. At a distance of 50AU around a solar type (G2V) star the temperature of a grain is then 40K. If the star is at a distance of 10pc the dust cloud will be fully contained in the 24" beam of the SEST. A simple calculation shows that a dust mass of $M_{dust} = 0.05/a$ Earth masses (a = grain radius in cm) produces a flux of 10mJy. Such a signal can be detected at the SEST with a reasonable amount of observing time. As we found for the Vega–type stars dust masses of up to 0.44 Earth masses (β Pic) (Chini et al. 1991), the detection of large (> 1mm) grains at 1300μm is quite likely. Preliminary observations at SEST for three of such candidates give flux densities between 8 and 15mJy and support the expectation that there is more evidence for planet formation coming up in the near future.

References

Chini R., Krügel E., Kreysa E., 1990, A&A 227, L5
Chini R., Krügel E., Shustov A., Tutukov E., Kreysa E., A&A 252, 220

2.2 The Future of (Sub)Millimeter Astronomy

(Sub)millimeter astronomy is rapidly advancing, because of a variety of continuing technological developments. This is the frontier of radio astronomy today. Receiver technology still has some way to go before fundamental (quantum noise) limits are reached, and sensitivities are rapidly improving. Receiver arrays (both heterodyne and bolometer) are now coming into service, offering data of improved quality obtained with greatly increased speed. Arrays of telescopes are becoming more commonplace, and a major new facility such as the Millimeter Array (MMA) which has been proposed in the U.S.A. would be a giant step forward (the MMA is the highest-priority item in the 1991 report of the Radio Astronomy Panel of the U.S. Astronomy & Astrophysics Survey Committee, and one of the highest overall in the Bahcall report). A southern hemisphere millimeter array was proposed three years ago at a specially convened meeting at ESO, following a SEST Users Meeting. Millimeter VLBI, still in its infancy, provides unprecedented angular resolution (20 μarcsec for an earth-diameter baseline). Large dishes and arrays above the atmosphere (in space or on the moon) will be the ultimate, but at huge cost. Because of the dramatic technical developments and explosive growth of this field, it is difficult (or even inappropriate) to speculate on the most important scientific advances which will take place in the next decades, although we can mention obvious extrapolations of present-day science and the potential capabilities of a large millimeter array.

Probably the most important recent discovery in the field was the detection of the CO (3-2) line in IRAS 10214+4724, an extraordinarily luminous galaxy at a redshift of z = 2.3. This was quickly followed by detections at millimeter wavelengths of other transitions of CO, neutral carbon fine-structure lines, and thermal emission from dust (fig. 24). Similar detections are now being made in objects at redshifts as high as 4.7, and with a large array similar galaxies at $z \sim$ 10-20 (the epoch of first galaxy formation?) may be detectable (fig. 25). Thus it appears that a new and totally unexpected window is being opened up on the very high-redshift Universe.

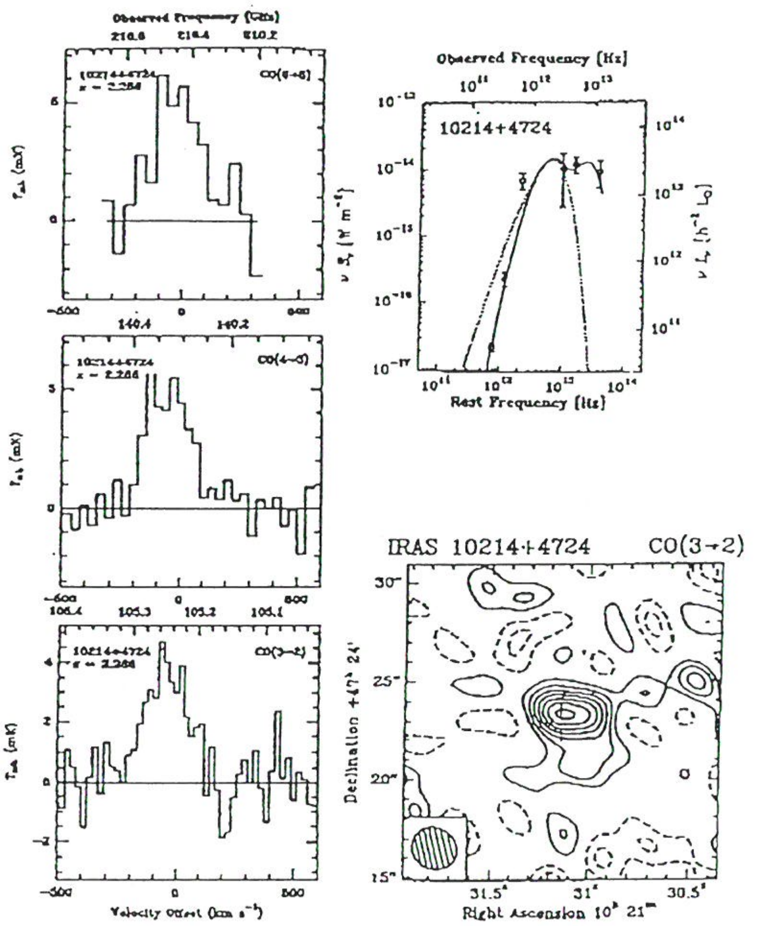
Because these emission processes are free of extinction, non-exotic and relatively well understood, they provide reliable estimates of densities, temperatures, and masses. Radio spectroscopy allows, in addition, measurement of systemic redshifts with high precision, and these redshifts are so high that they represent the expansion of the Universe in its purest form. If a sufficient number of luminous galaxies with thermal radio lines can be observed at high redshifts, millimeter observations have the potential of providing important new information on the expansion and geometry of the Universe.

These studies are best done in the millimeter region. At these redshifts the 21 cm line of neutral hydrogen is shifted to meter wavelengths, where there is considerable man-made interference, increased galactic radio noise, ionospheric perturbations of array phases, and insufficient bandwidth to compete with the millimeter band in sensitivity. In addition, CO and CI are intrinsically much stronger than HI. Also, most molecules have a ladder of spectral lines rather than the single HI line, so there always likely to be a line shifted to an easily observable wavelength no matter what the redshift. Finally, the very steep and favourable K-correction along the Rayleigh-Jeans portion of the spectrum (fig. 25) more than compensates for source brightness decreasing with distance; the flux density observed at a fixed wavelength varies little with redshift until the peak of the Planck curve is shifted past that wavelength, allowing continuum imaging of luminous galaxies out to redshifts of $z \sim$ 10-20. Because of the redshifts, one can do submillimeter astronomy at millimeter wavelengths, without requiring submillimeter technology or a very high altitude site. In conclusion, this will undoubtedly become a major new area of distant-Universe research, **and it is best done at millimeter wavelengths.**

Aside from this new high-redshift frontier, the great sensitivity and resolution of a large millimeter array will make possible major advances in many other areas of astronomy. It will yield images of dust and gas emission in active galactic nuclei and quasars with a resolution of about 100 parsec, and measure the Sunyaev-Zeldovich effect from clusters of galaxies to provide an independent determination of the Hubble constant. It will determine the masses and kinematics of optically obscured galactic nuclei with a resolution of a few parsec and image the distributions of a variety of molecules and isotopic species. Within the Galaxy it will observe stars of every spectral type and luminosity class, measure their photospheric emission and temperature gradients, and determine positions with astrometric accuracy (an important link tying different fundamental reference frames together). Observations with 0.1 arcsec resolution will resolve protostars and circumstellar accretion disks as small as 10 AU and measure their density and velocity structure, and provide images of the chemical gradients in circumstellar shells that reflect the chronology of stellar nucleosynthesis and envelope convection. The submillimeter range is best to detect planets around stars, as the contrast between the planet and the star is highest on the Rayleigh-Jeans side of the thermal emission of the planet. Inside the solar system, such an array will probe the physics of particle acceleration in solar flares, image the atmospheric winds and temperature profiles of Venus and Mars, resolve the phosphine emission in the Great Red Spot on Jupiter, hydrogen cyanide on Titan, and volcanic emission on Io, and obtain unobscured images of cometary nuclei and asteroids.

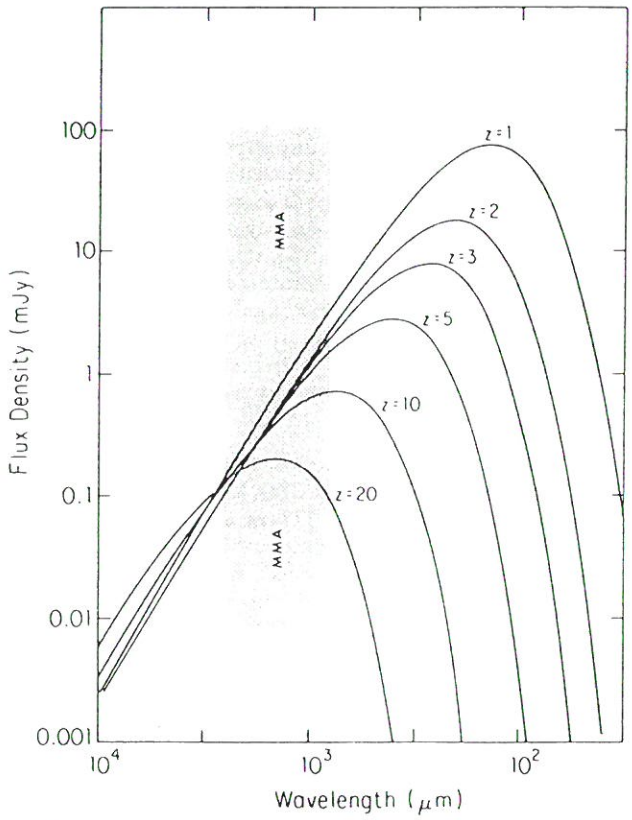
Thus, while (sub)millimeter astronomy is still to some extent a "specialist, technique-oriented" field today, it is clear that the next generation of (sub)millimeter radiotelescopes will enormously broaden the application of this wavelength region to a still wider variety of astrophysical problems, and make it more accessible to astronomers of all persuasions (optical/IR, theoretical, and others), as the VLA has done for centimeter-wavelength astronomy.

Figure 24



Left: CO (3–2), (4–3) and (6–5) lines in the high-z galaxy IRAS 10214+4724 obtained with the IRAM 30m telescope. Right top: FIR and submm continuum spectrum. Right bottom: Integrated CO (3–2) emission obtained with the IRAM interferometer consisting of 3 telescopes (530 m²) (contours: 1 mJy/beam).

Figure 25



The expected spectrum of the starburst galaxy Arp 220 as the object is moved to higher redshift. The shaded area indicates the frequency range of the MMA.

3. Existing and Planned (Sub)Millimeter Facilities around the World

3.1 Single-Dish Telescopes

Table 2 lists all of the world's millimetre antennae larger than 10m, in operation or planned. Only five of them operate below a wavelength of 1mm, and apart from the AT Mopra antenna ($\lambda \geq 2.6$mm) and the small telescope proposed for the antarctic, SEST is the only one in the south. In fact in the south SEST is the only fully dedicated millimetre antenna operating below a wavelength of 7 mm.

Mauna Kea is regarded as the best site for a millimetre telescope and special efforts have been made to optimise the telescopes on that site, JCMT and the Caltech instrument. In partcular the JCMT heterodyne receiver complement extends to 500 Ghz and a further receiver for the 650 - 690 Ghz band will soon be operational. In addition a bolometer array, SCUBA, will be on line early next year. This is actually two arrays, one of 37 pixels covering the 850 micron band and one of 91 pixels optimised for 450 microns. The JCMT and Caltech telescopes are occasionally linked to form a single baseline interferometer at either 230 GHz or 350 GHz, with a baseline of 164 m.

The largest millimetre telescopes are the IRAM 30m telescope on Pico Valeta in Spain and the Nobeyama 45m antenna on a much inferior site. Both will be superceded if the proposed U Mass - Mexican collaboration to build a 50m telescope in Mexico is successful.

3.2 Millimetre Arrays

Four millimetre arrays are in operation throughout the world (Table 3). The most productive instruments so far are the arrays in California. However, with the addition of the fourth antenna on Plateau de Bure, the IRAM interferometer's mapping speed and sensitivity are improved and we can expect some exciting results from this instrument in the near future. The IRAM array is currently operating at 2.6 mm but has the potential to work at 0.8 mm.

In the southern hemisphere, it is proposed to operate the Australia telescope at 2.6 mm but this will only be possible for a few nights per year. It is not yet clear how efficient the telescopes will be at this wavelength.

Thanks to some pioneering work at the BIMA (Hat Creek) array, it is becoming possible to asses the atmospheric phase fluctuations above individual telescopes by monitoring the total power from the receiver, before correlation. This technique will be important for successful operation of arrays at submillimetre wavelengths, and it is being studied by the CfA group building the SMA on Mauna Kea. Of course with arrays consisting of more than 3 antennae the use of closure phase becomes possible.

3.3 Receivers and Back-Ends

Several types of receivers may be used in millimetre and submillimetre astronomy, although today mixer receivers using superconducting tunnel junction receivers of the SIS (superconductor-insulator-superconductor) type are preferred. Such receivers, when properly optimised are capable of achieving noise temperatures within a factor of ten of the quantum limit - a fundamental limit inherent in the measurement process, which increases linearly with frequency. That is, the noise temperature is less than $10h\nu/k$ or equivalently less than 0.5 K/GHz. For ground based astronomy this may mean that the receiver noise is dominated by spillover and sky noise. In fact, depeding on the frequency and the site, the receiver performance may be such that no further improvement is warranted. A compilation of single sideband noise temperatures as a function of frequency is given in fig 26 (Phillips, 1994).

SIS receivers are produced in two basic types, waveguide mounted and quasi-optical, with waveguide receivers generally giving the best performance. However at high frequencies, quasi optical receivers are easier to construct and are more suitable for array applications.

The SEST began with alternative Schottky diode mixers, which have better total power stability and operate at the more convenient temperature of about 20K. However, by the end of the year all receivers will be SIS and the complement will extend over the bands: 80 - 120 GHz, 130 - 170 GHz, 210 - 270 GHz and 320 - 360 GHz (see tables 8 & 9).

An interesting development being driven in Sweden by the need for very high sensitivity at 119 GHz in the ODIN satellite is the extension of high electron mobility transistor (HEMT) technology to the 100 GHz band. This work is giving promising results and should simplify and reduce the cost of receivers for 100 GHz, an important consideration for a potential large millimetre array.

Receiver arrays are being used at some telescopes today. The NRAO antenna on Kitt Peak is being equipped with a 4 x 2 array and at the Quabbin antenna of U Mass., a 15 element array is operational at 2.6 mm. Because of cross-talk it is usual that the individual array beams are separated on the sky by at least one beam-width and so array measurements must be intespersed to fill in the gaps. This may be done by internal chopping - chopping between adjacent beams. Several other receiver arrays, both heterodyne and bolometer, are under development or planned at various observatories.

The World's Largest Millimetre Telescopes

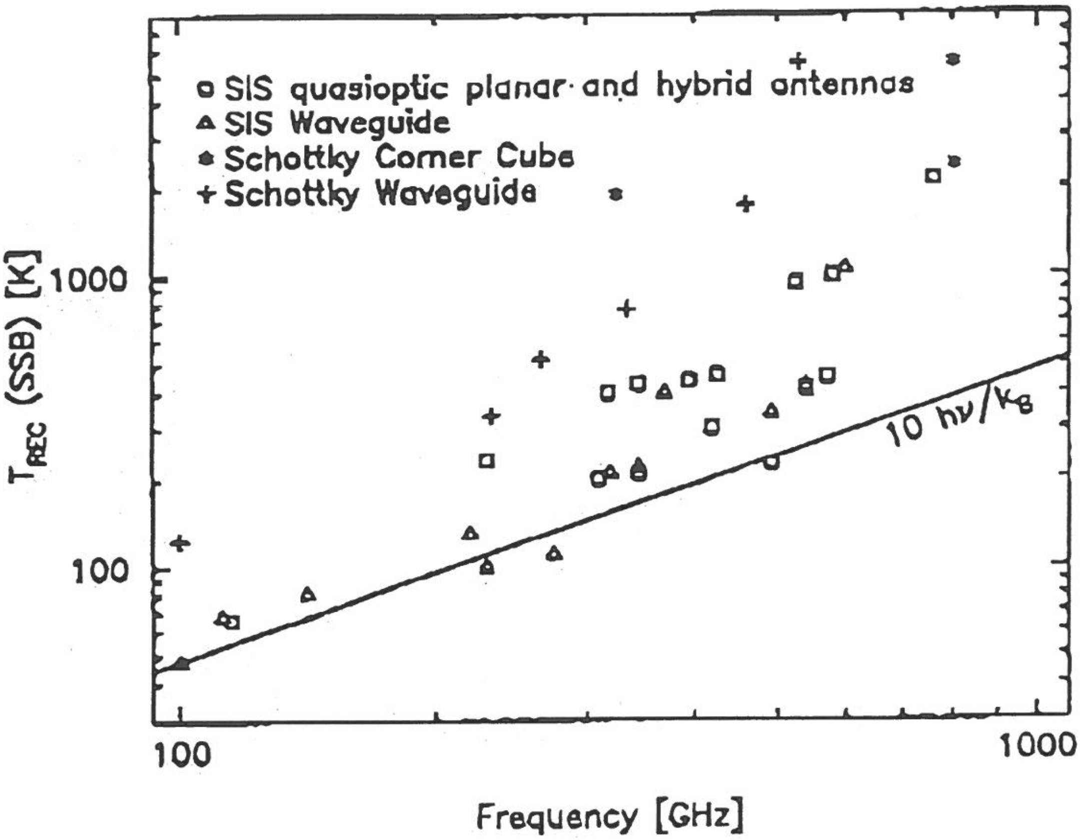
Table 2. Single antennae

Antenna	Location	Altitude (m)	Latitude	Diameter	Min λ (mm)	Area (m^2)
SMT Germany/USA	Mount Lemon	2800	32N	10	0.3	78
CalTech USA	Mauna Kea	4200	20N	10.4	0.7	85
Bangalore India		1000	13N	10.4	2.6	85
NRAO USA	Kitt Peak	1900	32N	12	1.3	113
U.Mass USA	Quabbin	310	42N	13.7	1.3	147
Itapetinga Brazil	Atibaia	800	23S	13.7	4.4	147
Metsähovi Finland	Kirkkonummi	150	60N	13.7	2.6	147
Daeduk Korea	Taejeon	1500	25N	13.7	7.0	147
Quing Hai China		3000	30N	13.7	7.0	147
Yebes Spain		900	40N	13.7	7.0	14.7
JCMT UK/NL/Canada	Mauna Kea	4300	20N	15	0.5	177
SEST Sweden/Germany	La Silla	2300	29S	15	0.8	177
Onsala Sweden	Råö	5	57N	20	2.6	314
Crimea Ukraina	Semeis	0	47N	22	4.5	380
IRAM France	Pico Veleta	2850	36N	30	1.3	707
Haystack USA	Westford	150	32N	37 (15%)	2.6	161
Nobeyama Japan		1350	36N	45	2.6	1590
Effelsberg Germany		370	50N	100 (4%)	2.6	280

Table 3. Millimetre and submillimetre arrays

Array	Status	Number of Antennas	Latitude	Instant. Collecting (m^2)	Min λ (mm)
Hat Creek USA	in operation	6x6m	41N	170	
Owens Valley	in operation	5x10.4m	37N	425	1.3
Owens Valley USA	proposed	10x10.4m		850	1.3
Nobeyama	in operation	5x10m		393	1.3
Nobeyama	for future	45m+5x10m	36N	1983	1.3
Nobeyama Japan	discussed	(10 to 15)x10m		785 to 1178	1.3
Plateau de Bure	in operation	4x15m	44N	707	0.8
Plateau de Bure France/Germany	proposed	6x15m		1060	0.8
Australia tel.	later phase	5x15m	30S	884	2.6
SMA USA	under construc. in Hawaii	6x6m	19N	170	0.35
NRAO USA	proposed New Mexico or Hawaii	40x 8 m	34N 19N	1767	≈1
NRAO USA	VLBA	8x25m		N.A.	7(3)

Figure 26



SIS quasioptic planar and hybrid antennas
SIS Waveguide
Schottky Corner Cube
Schottky Waveguide
T_{REC} (SSB) [K]
1000
100
10 hν/k_B
100
1000
Frequency [GHz]

4. The SEST Facility

4.1 Uniqueness and Role of the SEST

The SEST has a unique role, as the only large (sub)millimeter radiotelescope in the southern hemisphere. This is clear from section 3 above. As such, it provides unique opportunities for millimeter studies of the Magellanic Clouds and the southern Milky Way, and it is in the best position for studies of the galactic center, which passes almost directly overhead, unique objects such as Centaurus A, which is further south, and the closest barred spirals, which are also located in the southern hemisphere.

The only other facility which will overlap with SEST in some of its capabilities in the foreseeable future is the Mopra antenna of the Australia Telescope. The surface accuracy of the central 15m of this antenna is adequate for 3 mm observations. However, the site (Siding Springs) is inferior to La Silla, and both the site and the surface accuracy of the dish preclude observations at higher frequencies. There is also discussion in Australia about equipping the six antennas of the AT Compact Array with 3 mm receivers, although again the site is of marginal quality for observations at this wavelength. Such an array would of course provide complementary data, and so further enhance the importance of observations with the SEST. In the distant future, a (sub)millimeter telescope may eventually be established in Antarctica, where the operational conditions are brutal but the observational conditions ideal for true submillimeter work. Aside from these developments, the SEST will remain unique in the southern hemisphere for years to come.

The SEST has not only opened the southern hemisphere to (sub)millimeter observations, it has also provided a new window on the electromagnetic spectrum for ESO astronomers, as a complement to their optical and infrared observations. A glance through section 2 above gives an idea of the vitality of this new area of ESO astronomy.

4.2 History of the SEST, and Bilateral Agreements

On 26 June 1984 an agreement (Appendix 2) was signed between ESO and the Swedish Natural Science Research Council (NFR) for the installation and operation of the Swedish-ESO Submillimeter Telescope. The total capital cost was to be DM 9.6m (1983), including telescope, building, and initial receivers, of which DM 6.1m was to be paid by ESO and DM 3.5m by Sweden. In the operational phase, four persons full-time were to be provided at the SEST by NFR (plus one full-time equivalent at Onsala) and three persons by ESO (plus one full-time equivalent in support by the general mountain staff), and observing time was to be split 50-50 between Sweden and ESO. NFR was to be represented in these matters by the Onsala Space Observatory of the Chalmers Technical University (CTH) (Appendix 4). The Swedish-ESO agreement was to run for a period of 15 years, *i.e.* to 26 June 1999, with discussion of possible prolongation to take place two years before that date.

Also on 26 June 1984 ESO contracted with the Institut de Radio Astronomie Millimétrique (IRAM) for the construction of the SEST (Appendix 3), with main subcontractors in French and German industry. IRAM was to include one additional telescope in the existing manufacturing contracts for the three 15 m Plateau de Bure interferometer telescopes. As the interferometer telescopes are moveable, a separate contract was negotiated for the construction of a pedestal for the SEST.

The telescope was completed on 13 March 1987 (provisional acceptance), and "first light" was achieved on 24 March. Astronomers from the community were invited to submit proposals for observations with the SEST during the commissioning phase in 1987-8, and regular scheduled observations began on April 1, 1988.

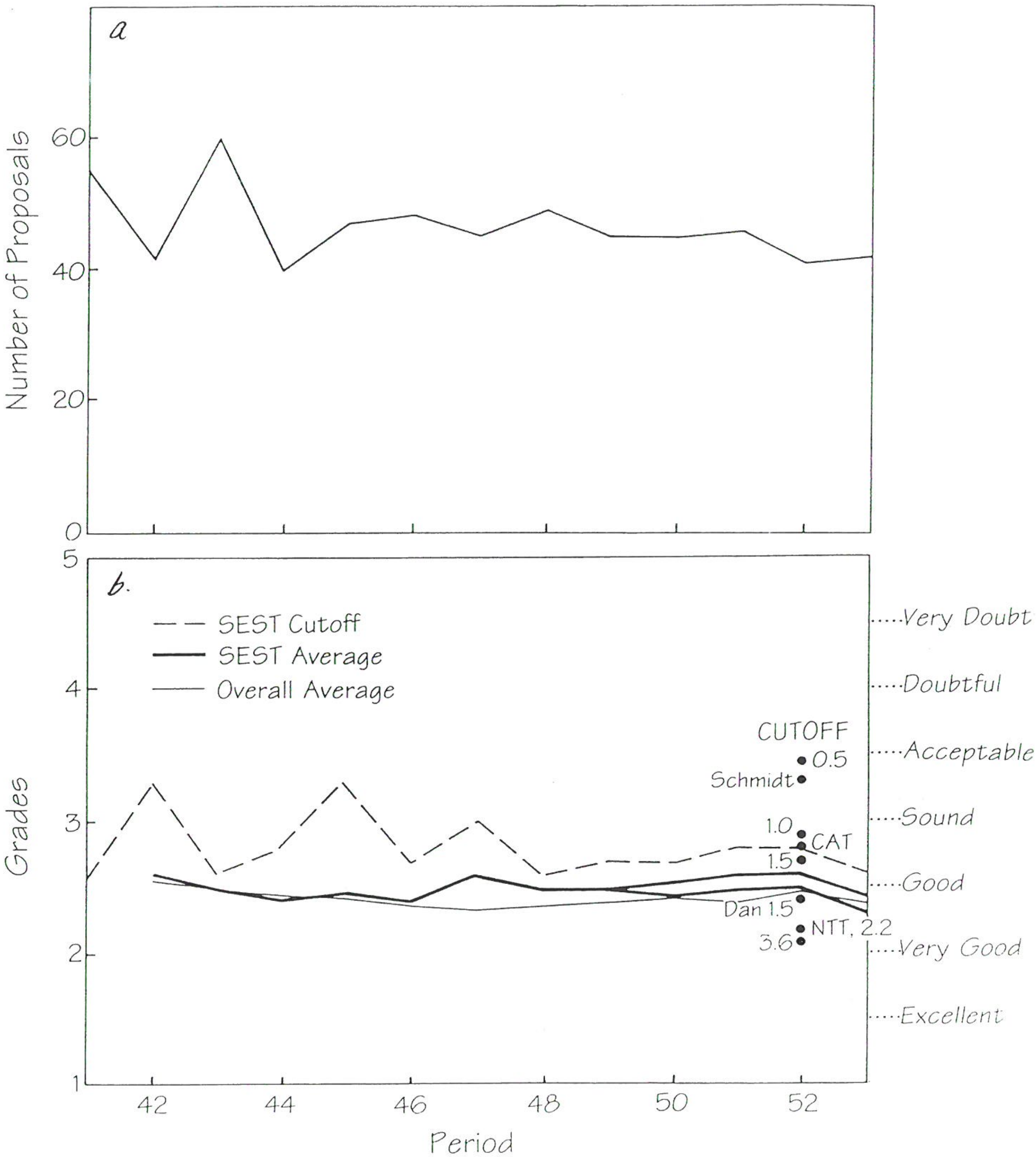
Since then there have been a few modifications and additions to the original agreements. An exchange of letters between the NFR and ESO and between the Onsala Space Observatory and ESO provided the basis for the day-to-day management. And, on 6 June 1990, an agreement was signed by the NFR, ESO, and CTH whereby CTH would take over all the obligations entered into by the NFR in the original agreement with ESO (Appendix 5). This year, due to internal reorganizations in Sweden, this latter agreement may be reversed, and responsibility on the Swedish side for SEST will once again be in the hands of NFR; the relevant agreement should be signed before the Swedish fiscal year begins on 1 July.

4.3 Demand for Observing Time, OPC Grades, and Scientific Productivity of the SEST

Figure 27a shows that the number of proposals for the SEST has not changed significantly with time. The average oversubscription factor for the SEST is 2.2, similar to that of other large (sub)millimeter telescopes (Table 7). It is lower than the figure of 3-4 typical of large optical telescopes, but this is misleading, as there is an enormous difference in observing efficiency. The SEST operates 24 hours a day, with astronomical observations occupying fully 58% of the year (*i.e.*, 58% of 365 x 24 hours); if it were operated like an optical telescope the oversubscription factor would be over 4. (For the major La Silla optical telescopes, assuming an average 9-hour night with losses of 17% (bad weather) and 4% (technical downtime), the observing efficiency is less than 30%. Benvenuti (1992 ECF Newsletter No. 17, p. 26) quotes an observing efficiency of about 60% for the IUE satellite, 36 % for the HST, and considerably less for the NTT).

The OPC grades for SEST proposals have also remained roughly constant over the 6-year life of the telescope. Figure 27b shows the average OPC grade and cutoff for the SEST compared with the other ESO telescopes. The SEST OPC ratings are close to the average ratings for all ESO proposals (which are dominated by the larger optical telescopes). The cutoff rating for the SEST has also not changed significantly with time. The fact that the SEST has a lower cutoff than the large optical telescopes is due in part to differences between the average grades given by different OPC members, and in part to the great efficiency of the SEST compared with optical telescopes as mentioned above.

The abundant scientific productivity of the SEST is evidenced by the summary of results in Section 2.1 above, and the (partial) list of publications in Appendix 1.


a
Number of Proposals
60
40
20
0
b.
SEST Cutoff
SEST Average
Overall Average
Grades
5
4
3
2
1
CUTOFF
0.5
Schmidt
1.0
CAT
1.5
Dan 1.5
NTT, 2.2
3.6
Very Doubt
Doubtful
Acceptable
Sound
Good
Very Good
Excellent
42
44
46
48
50
52
Period

4.4 Staffing and Costs

As stated in section 4.2 and Appendix 2, ESO's share of the capital cost of the SEST telescope (excluding receivers) was DM 5.6m (1983), which corresponds roughly to DM 7m (1994). This compares with capital costs for the NTT and 2.2m telescopes of about DM 39m and DM 8m (1994) respectively (the 2.2m cost includes only ESO's share), to which should also be added relevant labour costs within ESO.

The budgeted running costs of the SEST facility (excluding salaries, La Silla support, and visiting astronomer costs) have averaged DM 0.4m per year over the period 1988 to 1994 (DM 0.2m to ESO). This includes both operations (DM 0.13m) and development (DM 0.27m)).

The ESO-supplied personnel include the original three persons at the SEST and one full-time equivalent in support by the general mountain staff as specified in the Swedish-ESO agreement, the later addition of one operator, and a fraction of a full-time equivalent in scientific and administrative support at Garching. The total cost to ESO of these personnel is approximately DM 0.6m per year.

To these costs must be added the observing trips and La Silla accommodation paid by ESO for visiting astronomers to the SEST (about DM 0.2m per year), and the *incremental* cost of general support for the SEST facility provided by the La Silla infrastructure (cars, food & accommodation for ESO-supplied SEST staff, administration, communications, etc.), which is estimated at about DM 0.3m per year. Thus, the total cost to ESO of the SEST is about DM 1.3m per year. This is about 2.6% of the total ESO budget, excluding the VLT and VLT-related salaries. Or, considering just expenditures in Chile, the SEST costs are about 3.5% of the La Silla budget.

If publications are anything to go by, then, the SEST is relatively productive, as observations during the ESO time on SEST generate about 5% of all publications which are based on observations at ESO telescopes. Probably a more valid measure is the quality, nature and uniqueness of the scientific results from the SEST, and these can be judged from the contributions in Section 2. The high relative cost-effectiveness of the SEST is best seen in the comparison with other similar facilities in Section 4.6.

It should be noted that the SEST operation has been praised for its efficiency and user-friendliness; this is due in no small measure to the fact that it is run by a small team *dedicated 100% to the SEST* – an operational model which is now being considered for other ESO telescopes.

4.5 Present Technical Status

Telescope.

The panels of the main reflector consist of a carbon fibre - aluminium honeycomb - carbon fibre sandwich, covered on the reflector side by a film of aluminium foil protected by a thin layer of teflon. The Al-teflon film is fabricated in rolls and glued to the carbon fibre. The process uses the final accurate mould and the foil is sucked onto to the surface under vaccuum and the panel is glued on top, the glue taking up any small residual imperfections on the carbon fibre surface. IRAM has serious problems with the panels on the Plateau de Bure telescopes. The plastic layer gets damaged, mainly by ice particles during snow storms, and the aluminum layer corrodes. The climate on La Silla is more benign, and SEST show significantly less damage than the IRAM telescopes. The plastic layer on the SEST panels gets damaged mainly by impacts with dust particles during high winds. This damage can be kept under control by yearly inspections during which the damaged areas are covered with plastic stickers. Recently damage to the edges of several panels has been discovered. These are more serious since water can penetrate under the plastic layer and damage a large part of the panel. One panel will eventually have to be replaced. The edge damage to the other panels was discovered in time to cover the affected areas with stickers.

The pointing accuracy of the SEST is presently 3" rms, which is worse than originally specified, and causes problems especially during observations at 0.8 mm, where the beam size is 15". The pointing sometimes changes by more than 10" while tracking over a period of hours, and the exact cause of this has yet to be determined. Tests with inclinometers show that the tilt of the telescope axis changes over a 24h interval, probably due to varying illumination of part of the telescope by the Sun. The output of the inclinometers has been included in the fit of data from pointing runs, but without improving the pointing rms. A concerted effort is underway to understand the SEST pointing problem. Part of the telescope structure will also be covered to find out if this improves the pointing.

Receivers.

The SEST is presently equipped with a bolometer working in the 1.3 mm atmospheric window, and spectral line receivers consisting of dual polarization Schottky receivers covering the 3 mm atmospheric window, and single polarization SIS receivers covering the 1.3 and 0.8 mm windows. The spectral line receivers are tuned under computer control from the control room - a unique feature of the SEST. With some experience the observer is able to tune without staff assistance. A change of frequency normally takes 5 to 10 minutes. The parameters for the receivers are given in Table 4.

The bolometer can be used either for photometry or mapping in a dual-beam scanning mode with the data later restored to an equivalent single-beam observation using the NOD2 package. Its sensitivity is nominally 200 mJy $s^{-1/2}$ $beam^{-1}$. It is possible to switch between bolometer and spectral line observations from the control room. The bolometer requires liquid Helium and also has a ^3He refrigerator. It has to be refilled with Helium and the ^3He has to be recycled every day, a process that takes about 4h.

Table 4: SEST Receivers

Receiver	Tuning range (GHz)	Receiver temperatures (SSB)
0.8 mm	320–360	300–450
1.3 mm	215–270	250–450
3 mm	80–116	200–350

The 3 mm Schottky receiver is cooled by a closed cycle system which normally only requires maintenance once per year. The 1.3 mm receiver has a hybrid cooling system and has to be filled with liquid Helium once per week. The 0.8 mm receiver is cooled with liquid Helium in an open dewar, and has to be filled with Nitrogen and Helium every day.

The 0.8 and 3 mm receivers are working well without any major problems. The 1.3 mm receiver (on loan from the Harvard-Smithsonian Center for Astrophysics (CfA)) was out of service from July 1993 to March 1994 due to a series of technical problems: vaccuum leaks, a mechanical problem with the backshort of the mixer, and a break down of the SIS junction. The receiver now has a better junction which gives an improved receiver temperature. The tuning system that came with the receiver was not very user friendly, and both hardware and software was redesigned and implemented by the SEST staff.

The local oscillator (LO) chains are complicated and involve multipliers and phase lock loops to scale the maser reference frequency to the final local oscillitaor frequency. A minor problem at the SEST is the artificial broadening of the narrowest spectral lines which is caused by instability in one of the multipliers. Of course, the multiplier concerned is the most expensive in the chain but it must be replaced in all receivers.

Spectrometers.

Three Acousto Optical Spectrometers built by the University of Cologne, are used as backends for spectral line and sometimes continuum observations. Two of the AOS's cover a wide band (1 GHz), with lower resolution, the third one covers a narrow band (86 GHz), but has a higher resolution. It is possible to observe with two spectrometers simultaneously, connected either to one or two receivers. The 3 and 1.3mm receivers can be used simultaneously with various combinations of the spectrometers.

The laser diodes of the AOS's have a life time of approximately one year. A replacement includes realigning of the optics, which can take up to a week of work and has to be made during longer maintenance periods. The behaviour of the AOS's has to be monitored constantly (frequency response, resolution etc.) and corrections have to be made to the data. They are very temperature sensitive and are situated in a temperature controlled room. The Cologne group is presently improving the design of the optics and the power supply of the laser diodes. Better diodes may also become available in the future.

Control System, Data Handling and Interfaces.

The telescope and associated instrumentation are controlled by two networked minicomputers: a Hewlett Packard 1000/A900 and an HP1000/A600. The A900, the main computer, is used for general purpose instrument control and data reduction. The A600 (a smaller version of the A900) is dedicated to data acquisition from the spectrometers. The two computers are linked by ethernet.

The HP 1000 computers, now obsolete, will be replaced by HP 7000 work stations, and the telescope and instrument control system will be replaced by a modern bus system of the VME type. The telescope CAMAC bus has been replaced by a new system designed by SEST engineers and the rest of the control system will be adapted according to recent developments at Onsala to control the 20m telescope and its user interface. The job is being tackled in a modular way, and different modules are being replaced sequentially to avoid a lot of 'down time'. The replacement will be complete within two years.

For data reduction, there is an on-line package, DRP, which was specially written for the SEST. In addition, the more sophisticated CLASS system is running on the HP work station, and will be available on-line once the change to work stations is complete. Use of CLASS 'on-line' today involves transfer of data to the workstation, which slows down the HP computer.

All data taken at SEST are stored on nine track computer tapes that are kept in the SEST control building (a catalogue of all observations made with the SEST is accessible electronically. The archived data are kept on 9 track computer tapes in HP FST format. To make copies it is necessary to load the datafile to disk and produce a FITS tape. The tapes from 1988 are now more than 5 years and in some cases there may be read problems.

Interfaces with the community are provided by an electronic bulletin board, e-mail with the SEST team, the Users manual which has been widely distributed, periodic articles in The Messenger, and Users Meetings which have taken place about every two years.

4.6 Comparison with other Similar Facilities

Figure 28 and tables 5-10 show a comparison between the SEST and the other major (sub)millimeter telescopes around the world. The major points to note are the following:

(a) The SEST is a cost-efficient facility. The original capital cost was much less than that of the JCMT (Table 5) for similar technical specifications, and the operations and development budgets are only about one-quarter, and the total manpower about one-third, of that at each of the other facilities (Table 6). The operational efficiency, on the other hand, compares well with these other facilities, and demand for observing time is similar (Table 7).

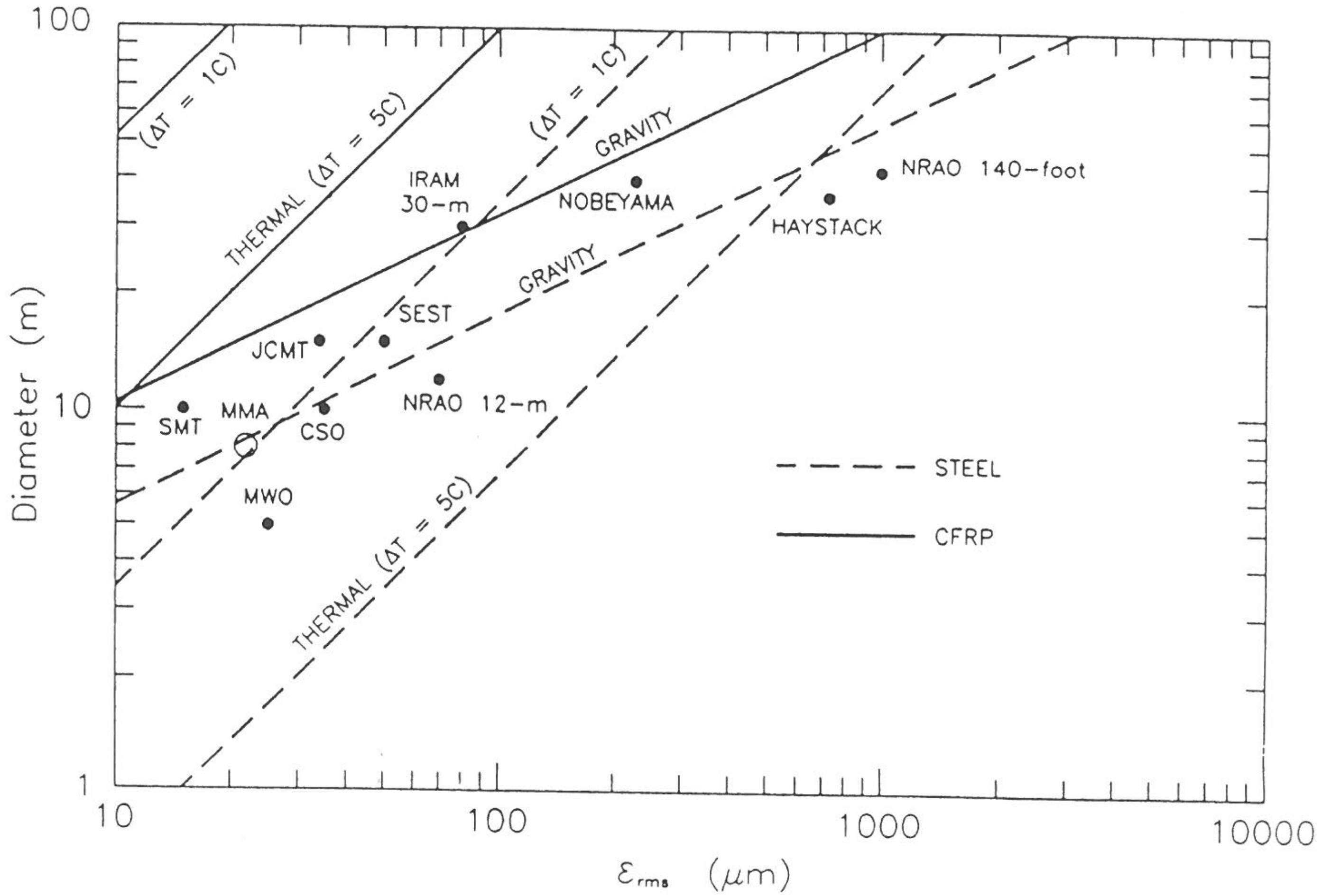


Figure 28 . A plot of antenna diameter vs. rms surface error, showing physical limits to the precision that can be attained.

Table 5

Telescopes & Sites

	SEST	JCMT	IRAM 30-m	Kitt Pk. 12-m
Telescopes				
Diameter	15 m	15 m	30 m	12 m
Surface Accuracy (rms)	$\sim 70\,\mu m$	$\sim 30\,\mu m$	$\sim 75\,\mu m$	$\sim 75\,\mu m$
Pointing Accuracy (rms)	$\sim 3''$	1–2″	$\sim 3''$	$\sim 4''$
Nutating Subreflector	No	Yes	Yes	Yes
Cost (1994 mDM)	~ 13	~ 60	~ 33	—
Sites				
Location	La Silla (Paranal)	Mauna Kea	Pico Veleta	Kitt Peak
Altitude (m)	2400 (2400)*	4100	2500	1900
PWV (mm) (Best + Worst Season)	2.2–6.7 (1.8–4.5)	~ 2–3	~ 4–10	~ 3–10
Wind (m/s) (median)	5.2 (4.8)*	—		—

* Hotel area

Table 6

Budgets & Manpower

	SEST	Others*
Budgets (excl. Salaries)		
Operations Budget kDM	130 + 300 †	1700
Development Budget kDM	270	1200
TOTAL kDM	400 + 300 †	2900
Personnel		
On-Site Personnel	10	29
Remote Personnel	2	4
Receiver Development	2	7
TOTAL	14	40

* Average of JCMT, IRAM 30m, Kitt Pk. 12m.

† Approximate incremental cost of support from the La Silla infrastructure.

Table 7

Operations

	SEST	Others*
Oversubscription (Req./Sched. Time)	2.2	2.1
Telescope Usage (% of full year)		
Scheduled Maintenance etc.	32%	32%
Technical Downtime	3%	3%
Weather Downtime	7%	13%
Observing	58%	52%

* Average of JCMT, IRAM 30m, Kitt Pk. 12m.

Table 8

Receivers

	SEST	JCMT	IRAM 30-m	Kitt Pk. 12-m
Heterodyne 7 mm			43 GHz HEMT (VLBI, holography)	
4 mm			86 GHz Schottky (for pointing)	70–90 GHz SIS 2-Ch. T_r ~ 100K SSB
3 mm	80–116 GHz Schottky T_r ~ 200–350K SSB		83–115 GHz SIS 1-Ch. T_r ~ 75K	90–116 GHz SIS 2-Ch.
2 mm			128–170 GHz SIS 1-Ch. T_r ~ 80K DSB	130–170 GHz SIS 2-Ch.
1.3 mm	215–270 GHz SIS T_r ~ 250–450K SSB	210–280 GHz SIS 1-Ch. T_r ~ 150K DSB	200–270 GHz SIS 1-Ch. T_r ~ 100–160K SSB	200–265 GHz SIS 2-Ch.
1 mm				260–300 GHz SIS 2-Ch.
0.9 mm	320–360 GHz SIS T_r ~ 300–450K SSB	320–375 GHz SIS 1-Ch. T_r ~ 200K DSB	330–350 GHz SIS T_r ~ 50K DSB	
0.6 mm		460–490 GHz SIS 1-Ch. T_r ~ 250K DSB		
0.4 mm		650–720 GHz SIS 1-Ch. T_r ~ 1000K (MPE arrangement)		
Bolometer	Bolometer 1-Ch. 1.3 mm	Bolometer 1-Ch. 0.35–2 mm (7 filters)	Bolometer 1-Ch. 1.3 mm	—

Table 9

Receiver Developments/Plans

	SEST	JCMT	IRAM 30-m	Kitt Pk. 12-m
Heterodyne	80–120 GHz SIS 1-Ch. T_r ~ 100K SSB 1994 130–170 GHz SIS 1-Ch. T_r ~ 150–200K SSB 1994	Upgrade existing receivers Wideband SIS 450–500 GHz and 700 GHz 1994/5	Upgrade 3 mm SIS	Upgrade existing receivers to broader BW
	SIS Array (16 beam) 1.3 mm under study	SIS Arrays — under study (8 Beam; eventually 64-beam at 345 GHz)	SIS Array (7–9 beam) 1.3 mm ~ 1997	SIS Array (8 beam) 220–240 GHz 1994 SIS Array (32 beam) 220–240 GHz under study
Bolometer		Bolometer Array (SCUBA) 37-beam (850 μ) 91-beam (450 μ) 1994 (~ 4–5 mDM)	Bolometer Array 37-beam (1.3 mm) 1994/5	—

Table 10

Backends

	SEST	JCMT	IRAM 30-m	Kitt Pk. 12-m
Present	3 AOS (2 1000 MHz) (1 86 MHz)	1 AOS (rarely used)	1 AOS (500 MHz)	
			3 Filter Banks (2 512×1 MHz, 1 256×100 kHz)	6 Filter Banks (256×0.03 ... 2 MHz)
		"DAS" Correlator (2000 Chs. over 2000 MHz)	2 Correlators (2048 Chs.)	Hybrid Correlator (2000 Chs. over 2400 MHz)
Future		New Analog Syst. (for exgal. work)	New Analog Syst?	
		New Correlator	New Correlator (New chip)	New Correlator (GBT chip)

(b) The technical specifications of the telescope (50 μm surface, 2" pointing) (Figure 28, Table 5) compare well with most of the other facilities also. However, it has proven difficult to reach these technical specs in practice: the surface accuracy remains about 70 μm rms and the pointing is still only about 3" rms. Furthermore, the absence of a nutating subreflector is increasingly seen as a major limitation, especially in connection with the possibility of future receiver arrays.

(c) The site is comparable with the others (Table 5), but Paranal is better than La Silla, and a move to Paranal would certainly benefit higher-frequency observations with the SEST (*cf.* Section 5.6).

(d) The receiver complement covers the "workhorse" millimeter frequencies (Table 8), and so satisfies much of the demand for millimeter wavelength observing, although the receiver sensitivities could be further improved. It would also be desirable if bolometer observations could be made at more than one wavelength. The site limits observational prospects at the highest frequencies, and a move to Paranal would certainly help to open up this part of the spectrum.

(e) Developments elsewhere are focussed on arrays, both bolometer and heterodyne (Table 9), and at the moment that prospect seems to be precluded at the SEST by the lack of a nutating subreflector. These arrays will greatly increase observing efficiency and quality.

(f) The SEST has a basic suite of backends, three accousto-optical spectrometers, but the emphasis elsewhere has been more on digital spectrometers (autocorrelators), and the new receiver arrays (especially for spectral-line work) will demand much more powerful correlators (Table 10).

In summary, the SEST is an efficient and productive facility, with costs and manpower well below those of other comparable facilities in the northern hemisphere. However, its surface and pointing characteristics are not up to spec, and its receivers could be further improved. And it will certainly fall behind in the future if it does not match developments taking place elsewhere in receiver arrays.

5. Possible Future Development of the SEST

Thus, while the SEST has been and continues to be a cost-efficient and scientifically very productive facility, there are many improvements which can and should be made, especially in view of its unique position as the only large (sub)millimeter telescope in the southern hemisphere. And, given the new technical developments taking place at comparable northern facilities, plans (and new financial commitments) should be made now to similarly upgrade the SEST in order that it can remain competitive.

5.1 Telescope Improvements

Surface Accuracy and Maintenance

At present the surface accuracy of the SEST is about 70 μm r.m.s. whereas the design specification was 50 μm r.m.s. The individual panels are well within spec, at $\sim$ 15μm r.m.s., and the problem has been in accurately measuring and setting the overall surface. The main technique employed so far has been holography using the LES-8 satellite, but this satellite has not always been available, the time available during the SEST maintenance periods has been limited, and the low operating frequency gives rather poor resolution, so the results have been mixed.

There are alternative possibilities which can be explored. Scans of planets provide crude surface maps and efficiency factors. The accurate setting of the JCMT surface was done using near-field phase mapping with a transmitter located on the nearby UKIRT at an elevation of 9°. This method could also be tried for the SEST, using a transmitter on top of the 3.6m (the elevation is 12°, but the distance is very short (300 m)), or a more distant transmitter on one of the nearby mountains (although in this case the elevation would only be $\sim$ 3° at most). These efforts will involve some extra cost, particularly in time on the SEST, but they are important and should be undertaken.

The 176 surface panels are made of aluminium honeycomb material sandwiched between carbon fiber reinforced plastic skins. The reflector surface is formed by a layer of aluminium, protected by a thin transparent teflon sheet, bonded to the outer surface. These panels, like the telescope structure, were covered by a 5-year guarantee from M.A.N., which has by now expired. Overall, the surface is still in good condition, but there are a number of pinholes and scratches, a few bubbles, and several edges have lifted somewhat from the backing. The greatest damage has occurred to the lower panel, probably due to water flow and dripping from the subreflector. None of these problems are serious at the moment, and most are contained by the application of stickers, but the panels are beginning to show their age. The lower panel will be replaced with a new one, and it may be prudent for the SEST, together with IRAM, to purchase (from M.A.N., while the production line is still in operation) one complete set of panels (or at least one panel per ring) to serve as possible replacements for seriously damaged panels on the SEST and the five Plateau de Bure telescopes.

Pointing Accuracy

The design spec called for a pointing accuracy of 2" rms, and this has not yet been achieved. The accuracy achieved is about 3" rms, good enough for most observations at 3 mm but not at 1.3 mm. Ideally, pointing offsets should be obtained during observing runs from nearby calibration sources. A number of SiO masers, CO sources (circumstellar envelopes), and quasars (bolometer sources) are used as pointing calibrators, but unfortunately there are not enough of them in the southern hemisphere that are suitable for the SEST. It is difficult to use continuum sources given the sensitivity of the receivers and lack of a dedicated backend for continuum observations (these problems are obviously worse at higher frequencies). An additional possibility is to install a CCD camera to vastly increase the number of accessible pointing calibrators (at least for nighttime), although it uncertain how accurately the optical and radio axes can be aligned, especially in view of the homology corrections. More effort is now being put into trying to understand the pointing problems, and it may be necessary to invest more telescope time in this work (this means less time for astronomical observations, but ultimately it should improve the quality of the science that can be done). At the moment there are only two inclinometers, but more are on order. Alternatives such as laser gyros may also be considered.

Nutating Subreflector

It is widely agreed that the use of a nutating subreflector can greatly improve observations of almost all kinds, particularly continuum work and observations of broad (*e.g.* extragalactic) spectral lines (frequency switching is adequate for narrow spectral lines). At the SEST there is a focal plane chopper wheel which switches between two beams symmetrically displaced in azimuth to each side of the telescope axis, the beam separation being approximately 12 arcmin on the sky. However, a nutating subreflector is preferable for various reasons, one of the most important being that a bigger mirror is needed to accommodate an array, and this is far simpler with a nutating subreflector. (A balanced bolometer system has been developed at Berkeley which can be used without a nutating subreflector, but the balance is critical, the chopping distance is fixed, and the technology is difficult).

At the moment it is not known whether (and at what cost) the SEST can accommodate a nutating subreflector. Engineering studies must be commissioned to study this possibility. It should also be determined whether or not receiver arrays can be accommodated on the SEST without the use of a nutating subreflector, and these studies should proceed in parallel. As these studies will determine whether or not receiver arrays are feasible on the SEST, they should be undertaken with high priority.

5.2 Receiver Improvements

Upgrades of Existing Receivers

When the 3 mm Schottky receiver is replaced later this year, all heterodyne receivers at the SEST will be of the SIS type. However, further upgrades will be necessary if the SEST is to remain truly competitive. In particular, the 1.3 mm SIS receiver on loan from the CfA has given many problems (sec. 4.5), and should be replaced in the near future.

The SEST has been dependent on the research and development effort at Onsala Space Observatory. This works well but limited man-power at Onsala means that receiver deveopment has been relatively slow and the turn-around time in replacing receivers is measured in units of several years. Thus, given the rapid rate of development in milimetre receiver technology, this means that at any time some of the SEST recivers will be behind state of the art performance. This is true of any general user facility. The only easy way to improve the situation is to put more money into receiver development either by better supporting the Onsala effort with ESO money - say by hiring more experienced engineers - or by the more expensive route of commissioning receivers from other groups. In that way it would be more in line with the efforts at the JCMT, IRAM, or the NRAO 12m.

New Frequencies

With the addition this year of the new SIS receivers at 1.3 and 2 mm, the standard accessible bands in the (sub)millimeter range will be satisfactorily covered (Tables 8 & 9) for spectral line work. It would also be advantageous for a variety of scientific problems (*eg.* the Sunyaev-Zeldovich effect) if the bolometer covered more than one frequency. In principle the filters can simply be exchanged, but they are mounted in the cryostat and it would be simpler to change cryostat+filter, which still requires a trip to the focus cabin. Furthermore, sensitivity is lost unless the feed horn is also changed to match the wavelength, and the bolometer should also be optimized to the observing wavelength. Hence, the addition of other bolometer frequencies is non-trivial, and implies time and cost.

Receivers covering frequencies higher than those presently available on the SEST are not really justified by the atmospheric conditions at La Silla, but they would certainly be warranted if the SEST were moved to Paranal. The only addition proposed for lower frequencies is a 43 GHz receiver, to be used for VLBI (see below), monitoring SiO masers, redshifted CO searches, etc.

Receiver Arrays

Receiver arrays represent the next major step in instrumentation for (sub)millimeter telescopes, just as array detectors have brought about a revolution in optical and infrared astronomy. They will greatly increase the efficiency of all kinds of mapping and searching programmes. Even the 16-element heterodyne array being considered for the SEST would increase mapping speed by at least an order of magnitude, making some programmes feasible which would have previously not been considered. The arrays can also increase the *quality* of the data, as all elements experience the same sky at any given time, so that relative calibration is improved. The MPIfR group has found a surprisingly large improvement in going from single-channel bolometers to arrays; the sky is correlated in all channels, so the use of an array is tantamount to another level of chopping, and (for example) point sources can still be reasonably well observed even through clouds (one channel for the source, several simultaneously for the sky).

A receiver array consisting of a x b horns, each feeding its own receiver and spectrometer, has several advantages over the conventional, single channel receiver for mapping large molecular clouds. It increases the mapping speed by up to a x b times, by recording this number of pixels simultaneously and also by internal chopping, i.e. chopping to adjacent grid points. It also improves the quality of the maps because it takes the basic unit a x b map without repointing and through the internal chopping, it efficiently eliminates the sky background noise. A heterodyne array receiver for SEST would be built for the optimum frequency of 230 GHz, and would contain at least 4 x 4 pixels, followed by SIS mixers. An innovative LO control developed at Onsala controls the different LO levels to the mixers by means of an opto-electronic attenuator whose attenuation depends on its illumination. Chopping would be achieved by nutating the sub-reflector.

If a nutating subreflector is available on the SEST, a bolometer array could possibly be obtained from the MPIfR in Bonn. They are presently using a 7-channel system and a 19-channel prototype, and developing a 37-channel system for the IRAM 30m telescope. These are extrapolations of the original one-channel system built for the SEST, and the cost would not be large ($\sim 100 - 200$ kDM at most). The SCUBA array being built for the JCMT is far more expensive ($\sim 3 - 4$ mDM including salaries) because it is extremely ambitious technically, the objective being to be completely sky-limited under the *best* conditions available on Mauna Kea; the conditions at La Silla do not justify such an expenditure.

Backends and Computers

The spectrometer should be a digital autocorrelation system, of the hybrid type where the wide observing band is divided by a filter bank into several low bandwidth correlators operating in parallel. This type of 'hybrid correlator'is the most flexible system that can be used as a back end for the imaging array (it would also facilitate the kinds of observations that are done today with the SEST by providing better spectral resolution and baselines than the present narrow-band AOS). Several such correlators have been built for millimetre observatories, based on the correlator chip designed by Albert Bos of NFRA. This chip operates with a fast clock rate of about 60 MHz, allowing a maximum filter bandwidth of 30 MHz. A collaboration between the European VLBI network and Haystack observatory has been set up recently to investigate faster correlator chip designs for VLBI correlators, and the current concept, which will also be used in the SMA has a sampling rate of 160 MHz. SEST should capitalise on this development and also copy the correlator architecture, where possible. The system could be controlled by a dedicated standard HP work station of the type already purchased for the new (under development) telescope and receiver control system.

Contractual Arrangements

ESO itself has no technical expertise in these areas, and it is obviously desirable that as many of these developments as possible be undertaken by ESO's partner in the SEST project, the Onsala Space Observatory. That effectively amounts to "in-house" development of SEST facilities, with all the advantages that implies - in-house technical expertise, and dedicated long-term support and maintenance. However, there may be occasions when ESO and Onsala together decide that a particular development is best contracted out to another institute. This has already been done in the case of the SEST bolometer, which was built under contract by the Max-Planck-Institut für Radioastronomie, and the 1.3 mm SIS receiver is on loan from the Center for Astrophysics. A variety of possible arrangements can be considered, which may involve partial payment in observing time, operational support from the institute, etc.

5.3 Operational and Management Issues

Observing Modes

So far, the SEST has largely been operated in the "classical" observing mode (observing astronomer at the telescope), although some limited service observing has been carried out by the SEST staff. Remote observing was foreseen as a possibility from the outset, and it would be relatively straightforward given the nature of the dataflow, but in the absence of any strong motivation for it, it has not yet been pursued.

The main motivation for any change in observing modes comes from the variable atmospheric conditions, which call for some form of flexible scheduling. One straightforward possibility might be for the observer wishing to use the bolometer or 350 GHz receiver to come to the telescope for longer periods to wait for optimal conditions, with routine 3 mm backup programmes (perhaps Key Programmes or SEST staff programmes) running in the background.

Staff Requirements

As shown in Table 6, the SEST facility is extremely efficient in manpower compared with the other similar facilities in the northern hemisphere - 9 staff at La Silla (plus one full-time equivalent in support from the general mountain staff), compared with an average of 29 at the other facilities. In part this is due to economies of scale provided by the preexisting infrastructure on La Silla. And in part it is due to the modern design of the SEST facility. The SEST was designed to be operable remotely or by the visiting astronomer alone, and in particular it has the (possibly) unique feature that the receivers are remotely tunable - this has resulted in a substantial saving in manpower. Another element is the fact that at the JCMT at least two persons are required to be at the telescope at any one time as a safety factor because of the high altitude. So, for a variety of reasons, the SEST has been extremely economical in terms of manpower.

The move to a Santiago base may require an increase in the SEST staff. It is, of course, premature to discuss possible staffing requirements if the SEST is moved to Paranal.

The SEST-related staff remote from the observatory (*i.e.* at Onsala and Garching) is also much smaller than for other comparable facilities. In part, this is again due to economies of scale at Onsala, where similar receiver development goes on also in connection with the radiotelescopes there. It is also due to the fact that the SEST operation is far more low-key than some of the others: no formal newsletter, no standing committees, no external contracts to monitor. However, it is also due to the fact that less SEST-related receiver development is taking place. If the SEST is to be competitive with the other facilities in receiver development, there will have to be a considerable increase in personnel cost, as suggested above in sec. 5.2.

Revisions to the SEST Budgets within ESO

At the moment the budgetary environment within all of ESO is in the process of being revised. The guiding philosophy is one of "work packages", which will make the cost accounting for specific activities within ESO more straightforward and transparent. In the case of the SEST, there should be at most two "work packages": Operations (based in Chile), and Development (based in Europe). The Swedish budget is equal but separate. Each year the past expenditure is compared and the proposed budgets agreed and coordinated.

5.4 Very Long Baseline Interferometry

SEST has been used successfully in two millimetre VLBI experiments and has demonstrated the importance of its southerly location on the quality of the maps of equatorial sources (see fig 10 of 3C 279). We look forward to monitoring outbursts in AGN with the ESO optical telescopes at the same time as we follow their spatial growth with VLBI!

An interesting picture of the available high frequency VLBI antennas emerges when we realise that they mostly exist aroung the Pacific basin - in the high Andes, the volcanoes of Hawaii, the high plateaux of Arizona and California, the high mountain ranges of Japan and the slopes of the Himalayas. No other area of the Earth can supply such high altitude sites spread over a large area.

The Swedish side of the collaboration has already placed a hydrogen maser frequency standard on La Silla and has purchased a VLBA terminal which will be shipped to Chile in September/October. (Together the cost of these items amounts to around DEM 900k). They are also planning to build a dedicated local oscillator system for the 86 GHz VLBI receiver. In addition we need receivers for both 230 GHz (essentially a dedicated local oscillator) and 43 GHz (a full receiver) to complete the VLBI receiver complement.

5.5 230 GHz Survey Collaboration

Following the successful Columbia survey of the 115 GHz CO (1-0) in the Milky Way and Magellanic Clouds using a 1.2 m diameter radio telescope, a similar survey of CO (2-1) at 230 GHz with matching resolution is an important follow-up to facilitate fuller interpretation of the molecular data in terms of the physical conditions in the interstellar gas. Such large-area surveys at low angular resolution are useful, not only for studies of the large-scale distribution of molecular gas in the Galaxy and galactic structure, but also to provide essential preliminary information for more detailed studies using the much higher angular resolution of the SEST (in much the same way that Schmidt surveys support subsequent work at larger optical telescopes).

The Institute of Astronomy at the University of Tokyo has built a 60 cm diameter telescope for the purpose of making such a 230 GHz survey in the southern hemisphere. The survey will be conducted as a collaboration between the University of Tokyo, the Onsala Space Observatory, the University of Chile, and ESO. The telescope will be located on La Silla near the SEST. It will use the original 230 GHz SEST Schottky receiver, and will be operated by a graduate student from the University of Tokyo with backup support from the SEST team. The survey is expected to take five years to complete, and the survey data will be made generally available.

5.6 Possible Move to Paranal

The advantages of locating the SEST at Paranal are twofold:
(1) It would considerably increase the efficiency of observations with existing receivers on the SEST at the highest frequencies, and open the way to new receivers at still higher frequencies.
(2) If a millimeter array is eventually to be built at Paranal, the SEST could be one of its elements.

Statistics of precipitable water vapour (PWV) at La Silla and Paranal have been obtained at various periods over the last decade, using both sky radiance monitors operating in the thermal infrared and radiometers operating at 22 GHz. There has been some dispute between these two methods in the past, but it is believed now that the results have been reconciled. The statistics from the sky radiance monitors, as published in the VLT Site Selection Working Group Report (ESO/STC-110), are summarized in Figure 29 for La Silla and Paranal (even if the absolute values are not exactly correct, the relative values should be directly comparable). Reference to Figure 30, showing the atmospheric transmission as a function of PWV, illustrates the considerable advantage of Paranal at (sub)millimeter wavelengths. The ratio of median PWV between Paranal and La Silla in the winter months corresponds to a ratio in atmospheric transmission of almost four in the 0.4 mm band. Furthermore, the periods of high atmospheric transmission are more stable and longer at Paranal than those at La Silla, so making efficient use of good periods is far easier.

Figure 31 shows the terrain in the vicinity of Paranal. There are large areas of very flat terrain suitable for arrays of which the SEST could be an element, the highest of which are closer to Armazones.

Figure 29

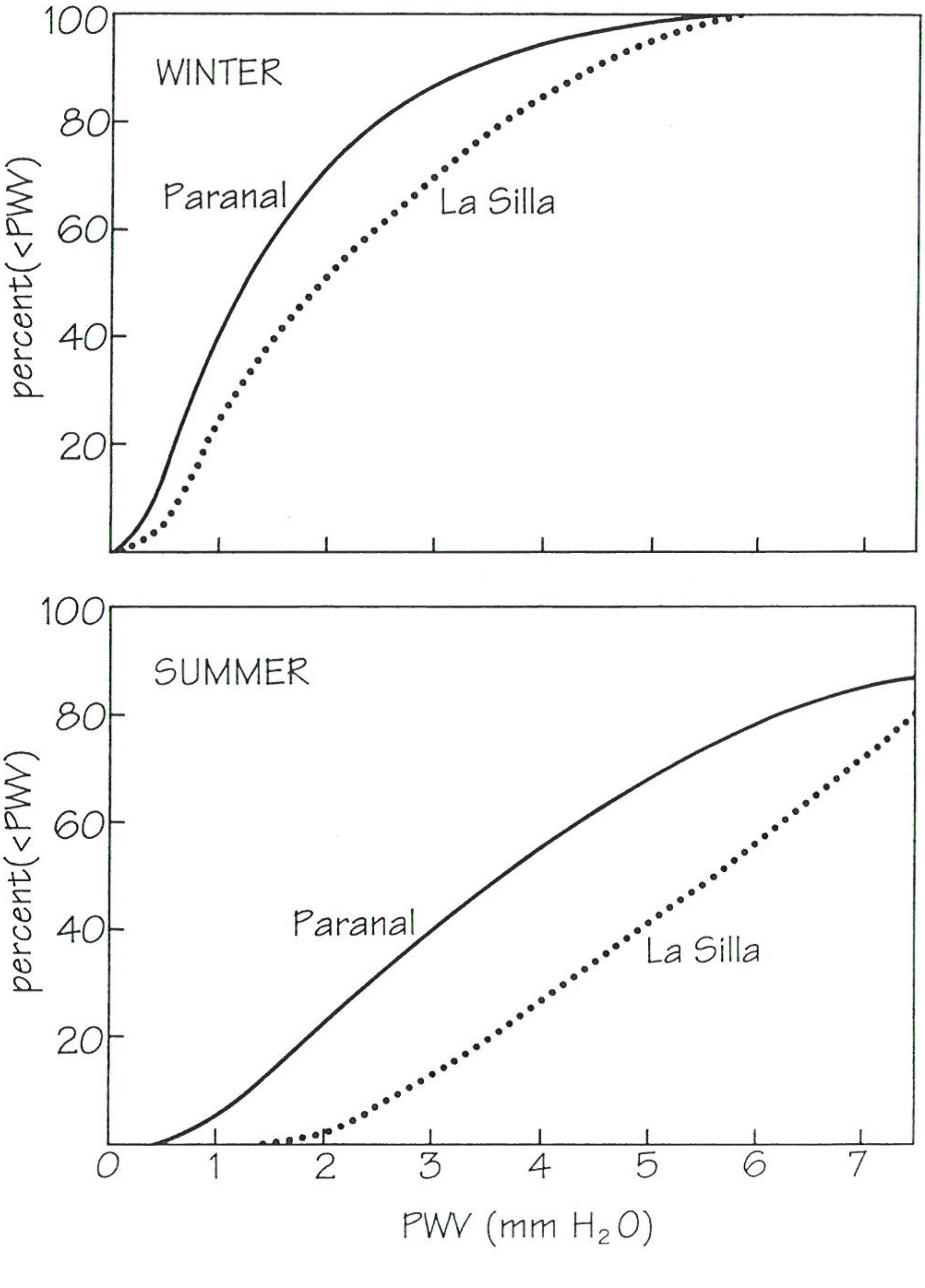
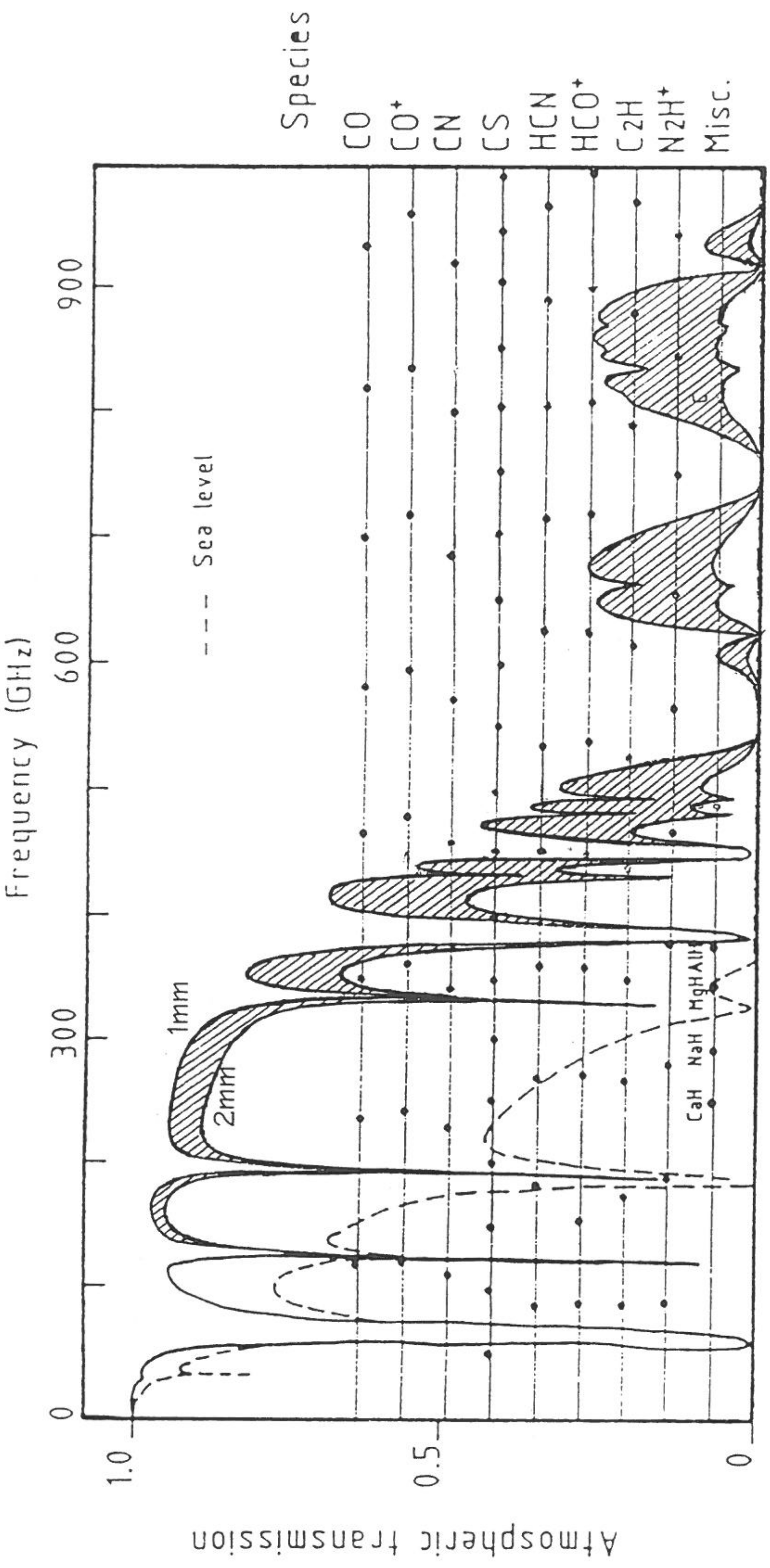
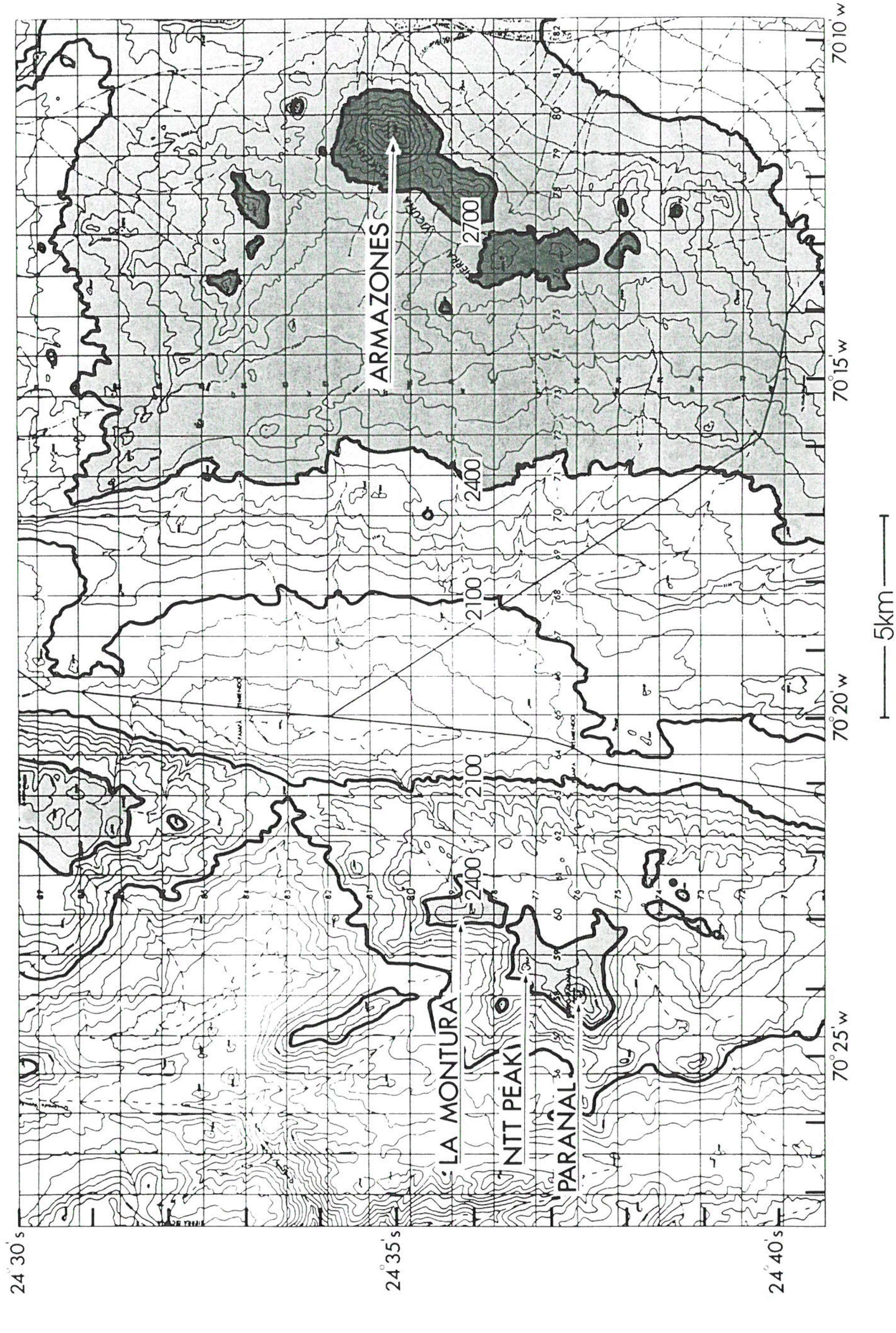

100
WINTER
80
Paranal
La Silla
60
40
20
percent(<PWV)
100
SUMMER
80
60
Paranal
40
La Silla
20
percent(<PWV)
0
1
2
3
4
5
6
7
PWV (mm H2O)

Figure 30



Frequency (GHz)
0
300
600
900
- - - Sea level
1mm
2mm
CaH
NaH
MgH
AlH
Atmospheric transmission
1.0
0.5
0
Species
CO
CO+
CN
CS
HCN
HCO+
C2H
N2H+
Misc.


ARMAZONES
2700
2400
2100
2100
2400
LA MONTURA
NTT PEAK
PARANAL
70°10'W
70°15'W
70°20'W
70°25'W
24°30'S
24°35'S
24°40'S
5km

The feasibility and cost of a move to Paranal have yet to be determined. In principle the move should not be too difficult, as the telescope panels and structure can be taken apart and reassembled. New foundations would have to be built, but this was a minor part of the original cost of the SEST. A new control building would also have to be provided, but if an array was foreseen, the control facilities could be combined. The figure of 2 mDM in Table 11 is a very rough estimate.

5.7 Estimated Costs of the Proposed Developments

Table 11 shows estimates of the costs of possible developments, in the following two categories:

(a) proposed near-term developments

These are developments which should be undertaken in the normal course of events in any case (the only exceptional item is the VLBI receiver and terminal upgrade, and this has been justified in Section 5.4 above), and the total cost is not much in excess of the usual development budget over a period of a few years (Table 6) - in fact, it is still less than that typically spent in just one year at the other major (sub)millimeter telescopes.

(b) possible longer-term developments

These are items which require further study and elaboration, and the bulk of the expenditure would be some years in the future. There are two main areas of proposed development: receiver arrays (which require the nutating subreflector and digital correlator), and the possible move to Paranal (to make higher-frequency observations feasible). If the SEST facility is to remain competitive with the other major (sub)millimeter telescopes, both of these developments should take place. Even after this expenditure of 6.5 mDM the SEST would still be by far the most economical of the (sub)millimeter telescopes. If ESO is serious about maintaining the SEST as a front-line facility, these possible developments should be given serious study.

Table 11. Estimated Costs of Proposed Developments (KDM)

	(a) Proposed near-term	(b) Possible longer-term
Panel Improvements		
New and Spare Panels	25	200
Pointing Improvements		
Laser Gyros		100
Nutating Subreflector		1,200 ?
Engineering Studies	30	
Receivers:		
Upgrades (230 GHz)	500	
New Bolometer Freqs.		100 ?
Bolometer Array		200 ?
SIS Array		1,200
Backends:		
Digital Correlator		1,500
VLBI:		
43 GHz receiver	100	
Mk IV upgrade	50	
Dedicated LOs for VLBI	75	
Move to Paranal		2,000 ?
Engineering Study	20	
TOTAL	800	6,500

6. A Possible (Sub)Millimeter Array at Paranal

6.1 A Southern Hemisphere Array

The rich harvest of results from millimetre astronomy amply justifies the construction of a much more powerful, next generation instrument, as argued in Section 2.2. The detection of CO at high redshift means that mm line astronomy will become a significant investigative tool in cosmology, provided we can detect many more high redshift objects in reasonable integration times and with sufficient spatial resolution. The recent mapping of the star IRC+10216 in rare molecules like MgNC and NaCl with the IRAM interferometer, shows the power of mm interferometry in delineating the chemistry of circumstellar envelopes. New studies of the star GG Tauri in ^{13}CO show the ability of mm interferometry to derive the kinematics of disks around pre-Main Sequence stars. Mosaic maps of galaxies like M51 show the potential of mm interferometry to map giant molecular cloud complexes in nearby galaxies.

In fact, nearly all objects studied in mm astronomy contain weak fine structure, unresolved with current mm telescopes. To resolve this structure, we need to use longer baselines, and to do so, we need more sensitivity. This can only be obtained with an interferometric array with a large collecting area.

A next generation millimetre telescope should, therefore, have a collecting area of about 10,000 square metres, comparable to that of the VLA, and around ten times greater than available at present. Scientifically, such an instrument should provide a quantum jump in present-day mm astronomy, and it should be able to open new directions in astrophysics (Sec. 2.2).

There is a strong case for siting this new instrument in the southern hemisphere because of the availability of good millimetre sites at high altitude and because many interesting Galactic objects are in the southern sky. These include the Galactic center and the entire central part of the MilkyWay, with most Galactic star forming regions, protostar outflows, compact H II regions, proto-planetary disks, circumstellar envelopes, and planetary nebulae. The southern sky also has the Magellanic Clouds and some spectacular galaxies - prototypes for their classes - as well as one of the nearest AGN, Centaurus A.

For practical operations, the major design goals should be reliability, robustness, and simplicity. A starting concept is an array with about 50 x 15m dishes (or 100 x 10m dishes) with 50 microns global precision, to be sited above 2000 m altitude on a site allowing baselines up to 10 km. Of course such an array does not have to be realised in one step. An interferometer, if designed correctly, is capable of useful operation from the moment that two (realistically three) antennae are constructed. Thus, a first step could be taken by a consortium of one or two nations, with some ESO support.

6.2 Possible International Collaboration

A project of this scale may best be undertaken as an international collaboration. There have already been several expressions of interest in the idea of a (sub)millimeter array in

Chile, for two main reasons: the northern hemisphere is (or soon will be) well populated by (sub)millimeter arrays of modest size (*cf.* Section 3), while there is nothing in the south (aside from the possible eventual operation of the Australia Telescope at 3 mm), and (b) Chile offers an excellent combination of good (sub)millimeter atmospheric conditions and large expanses of high, relatively flat, desert terrain.

The Nobeyama Radio Observatory (NRO) of Japan has been pursuing plans for an array of 50x10m antennas (the "Large Millimeter & Submillimeter Array", LMA), to be located somewhere in northern Chile, and site testing (starting with trials at La Silla and soon measurements at Paranal) is underway, in collaboration with Sweden.

The National Radio Astronomy Observatory (NRAO) of the U.S.A. has recently decided also to consider a Chilean site for its Millimeter Array (MMA), rather than focussing exclusively on U.S. sites as it had previously done. The MMA would consist of 40x8m antennas, at a cost of $120 million (1990).

In Europe, the French-German collaboration IRAM has considered the possibility of eventually moving the Plateau de Bure antennas to the southern hemisphere (Chile), perhaps at the end of the decade. Some years ago Sweden proposed a modest array to be located at Paranal, but realized that some form of international collaboration would be required. In the Netherlands, a discussion is currently taking place on the next steps for Dutch ground-based astronomy, and participation in a (sub)millimeter array, possibly at Paranal, is one of the two main contenders. Swedish-Dutch discussions presently center on the possibility of a 20 x 10m antenna array, which could be the starting concept for a much larger array to be built at Paranal. A European working group was formed two years ago to discuss these and other possibilities for the establishment of a southern (sub)millimeter array.

In view of the likely need for an international collaboration to realise a large (sub)millimeter array, Commission J of URSI has recently set up a Millimetre/Submillimetre Array Working Group under the joint chairmanship of Masato Ishiguro and Roy Booth. This group will address the topics of size, frequency range and international cooperation.

6.3 Support from ESO

The establishment of a (sub)millimeter array in the Paranal area would be mutually beneficial - to ESO as well as to the array consortium. It is clear from the SEST example how cost-effective it is to have access to a large pre-existing infrastructure. There are significant economies of scale, because beyond a certain point the incremental cost of providing support for an additional facility is not large. If a substantial (sub)millimeter array were to be built at Paranal, ESO would also benefit from these economies of scale - sharing resources and having access to particular technical expertise which may not otherwise be available. There would also be significant advantages to all parties from the concentration of scientific activities and interests, which would be sure to lead to productive cross-pollination and collaboration. Also, given ESO's large investment in southern-hemisphere astronomy, it would clearly be to ESO's advantage to have a large (sub)millimeter array available in the same hemisphere, preferably close to the large optical telescopes.

More concrete support from ESO (*i.e.* financial) should not be excluded, in view of the interest in many of the ESO member states in radio (including (sub)millimeter) astronomy. Active participation in a large (sub)millimeter array would promote related technical developments in these countries, in addition to providing observing opportunities with what could become the foremost facility of its type in the world.

ESO should therefore, in its own self-interest, at least be supportive of any initiatives to establish a (sub)millimeter array at Paranal. This support could (at present) range from a simple statement of encouragment and willingness to cooperate, which in itself would be politically helpful, to more substantial assistance by way of providing site data and taking part in or hosting meetings on the subject.

7. An ESO Working Group on (Sub)Millimeter Astronomy

Until now, the SEST facility has had no dedicated guiding body of representatives from the community, aside from a few Users Meetings which have been organized roughly every two years. By comparison, the JCMT has a standing Users Committee, and IRAM a Scientific Advisory Committee, in addition to their respective governing bodies.

It is proposed that ESO establish a Working Group on (Sub)Millimeter Astronomy. This Working Group would be comprised of experts in (sub)millimeter astronomy with a broad representation from the ESO community, and would make recommendations to ESO and the STC with regard to both the SEST facility itself and broader issues related to (sub)millimeter astronomy, including the possible establishment of a millimeter array in the Paranal area.

Some Publications in Refereed Journals Based on SEST Observations

1988

"SEST observations of CO(1-0) emission in ultraluminous infrared galaxies", Mirabel, I.F., Booth, R.S., Garay, G., Johansson, L.E.B., Sanders, D.B., 1988, A&A 206, L20.
"SEST CO(J=1-0) observations of carbon-rich circumstellar envelopes", Olofsson, H., Eriksson, K., Gustafsson, B., 1988, A&A 196, L1.

1989

"Dense gas in nearby galaxies. II. CS emission from spiral galaxies", Mauersberger, R., Henkel, C., Wison, T.L., Harju, J., 1989, A&A 226, L5.
"A search for HCOCN in molecular clouds", Gerin, M., Combes, F., Encrenaz, P., Turner, B., Wootten, A., Bogey, M., Destombes, J.L., 1989, A&A 224, L24.
"High spectral-resolution CO observations of NGC 6814 and NGC 7793", Brand J., Wouterloot, J.G.A., Becker, R., Stirpe, G.M., 1989, A&A 211, 315.
"The Swedish-ESO Submillimetre Telescope (SEST)", Booth, R.S., Delgado, G., Hagstrom, M., Johansson, L.E.B., Murphy, D.C., Olberg, M., Whyborn, N., Greve, A., Hansson, B., Lindstrom, C.O., Rydberg, A., 1989, A&A 216, 315.
"The molecular cloud content of early type galaxies. I. Detections and global properties", Wiklind, T., Henkel, C., 1989, A&A 225, 1.
"IRAS sources beyond the solar circle. I. CO observations", Wouterloot, J.G.A., Brand, J., 1989, A&AS 80, 149.

1990

"CO observations of very cold southern circumstellar shells and pre- planetary nebulae", Loup, C., Forveille, T., Nyman, L.-A., Omont, A., 1990, A&A 227, L29.
"The nucleus of NGC4945: a molecular mm-wave study", Henkel, C., Whiteoak, J.B., Nyman, L.-A., Harju, J., 1990, A&A 230, L5.
"Observations of 86 GHz SiO maser emission in late-type stars", Le Bertre, T., Nyman, L.-A., 1990, A&A 233, 477.
"COin the bipolar planetary nebula NGC3132", Sahai, R., Wootten, A., Clegg, R.E.S., 1990, A&A 234, L1.
"The discovery of high velocity CO-emission from the peculiar F-type supergiant HD101584", Trams, N.R., van der Veen, W.E.C.J., Waelkens, C., Waters, L.B.F.M., Lamers, H.J.G.L.M., 1990, A&A 233, 153.
"SiO and CO emission from carbon stars with silicate features and southern IRAS sources", Deguchi, S., Nakada, Y., Sahai, R., 1990, A&A 230, 390.
"Bright carbon stars with detached circumstellar envelopes - A natural consequence of helium shell flashes?", Olofsson, H., Carlstrom, U., Eriksson, K., Gustafsson, B., Willson, L.A., 1990, A&A 230, L13.

"A comparison of photospheric and circumstellar [HCN]/[CO]-ratios for bright carbon stars", Olofsson, H., Eriksson, K., Gustafsson, B., 1990, A&A 230, 405.
"H2 emission and CO absorption in Centaurus A: evidence for a circumnuclear molecular disk", Israel, F.P., van Dishoeck, E.F., Baas, F., Koornneef, J., Black, J.H., de Graauw, T., 1990, A&A 227, 342.
"CO(1-0) emission from luminous infrared galaxies in the southern hemisphere", Mirabel, F., Booth, R.S., Garay, G., Johansson, L.E.B., Sanders, D.B., 1990, A&A 236, 327.
"We 21: a WN 8 star in a planetary nebula", Duerbeck, H.W., Reipurth, B., 1990, A&A 231, L11.
"The evolution of the flux density of Supernova 1987 A at 1.3 mm", Biermann, P.L., Chini, R., Haslam, G., Kreysa, E., Lemke, R., 1990, A&A 236, L17.
"Molecular gas in cometary globules: CG1", Harju, J., Sahu, M., Henkel, C., Wilson, T.L., Sahu, K.C., Pottasch, S.R., 1990, A&A 233, 197.
"Arm and interarm molecular clouds in M83", WIklind, T., Rydbeck, G., Hjalmarson, A., Bergman, P., 1990, A&A 232, L11.
"Observations of CO emission from the nucleus of NGC 4945", Whiteoak, J.B., Dahlem, M., Wielebinski, R., Harnett, J.I., 1990, A&A 231, 25.
"IRAS sources beyond the solar circle. II. Distribution in the galactic warp". Wouterloot, J.G.A., Brand, J., Burton, W.B., Kwee, K.K., 1990, A&A 230, 21.
"CO in mergers. II. NGC 7252: the link between mergers and ellipticals", Dupraz, C., Casoli, F., Combes, F., Kazes, I., 1990, A&A 228, L5.
"A search for millimetre lines of HCN in comets Wilson 1987VII and Machholz 1988XV", Crovisier J., et al., 1990, A&A 234, 535.
"A comprehensive study of the peculiar spiral galaxy NGC 1808. I. Radio continuum and CO line observations", Dahlem, M., Aalto, S., Klein, U., Booth, R.S., Mebold, U., Wielebinski, R., Lesch, H., 1990, A&A 240, 237.
"Detection of 51 new 86 GHz SiO, v=1, J=2-1 masers associated with IRAS point sources", Haikala, L.K., 1990, A&AS 85, 875.
"Observations of CO isotopic emission and the far-infrared continuum of Centaurus A", Eckart, A., Cameron, M., Rothermel, H., WIld, W., Zinnecker, H., Rydbeck, G., Olberg, M., Wiklind, T., 1990, ApJ 363, 451.

1991

"CO observations of southern protoplanetary nebulae with optical counterparts", Bujarrabal, V., Bachiller, R., 1991, A&A 242, 247.
"IRAS 07027-7934: the link between OH/IR stars and carbon-rich planetary nebulae", Zijlstra, A.A., Gaylard, M.J., te Lintel Hekkert, P., Menzies, J., Nyman, L.-A., Schwarz, H., 1991, A&A 243, L9.
"Abundance and chemistry of interstellar HOCO+", Minh, Y.C., Brewer, M.K., Irvine, W.M., Friberg, P., Johansson, L.E.B., 1991, A&A 244, 470.
"CO J=1-0, 2-1, and 3-2 absorption and emissiontoward the nucleus of Centaurus A: probing the circumnuclear disk", Israel, F.P., van Dishoeck, E.F., Baas, F., de Graauw, T., Phillips, T.G., 1991, A&A 245, L13.
"Herbig-Haro jets and molecular outflows in L1617", Reipurth, B., Olberg, M., 1991, A&A 246, 535.

"CO J=3-2 observations of translucent and high-latitude molecular clouds", van Dishoeck, E.F., Black, J.H., Phillips, T.G., Gredel, R., 1991, ApJ 366, 141.
"Observations of stellar winds from hot stars at 1.3 millimeters", Leitherer, C., Robert, C., 1991, ApJ 377, 629.
"Molecular gas excitation in NGC 253", Wall, W.F., Jaffe, D.T., Israel, F.P., Bash, F.N., 1991, ApJ 380, 384.
"Peculiar molecular clouds in NGC 3256?", Aalto, S., Black, J.H., Booth, R.S., Johansson, L.E.B., 1991, A&A 247, 291.
"1.3 mm continuum emission from circumstellar envelopes", Walmsley, C.M., Chini, R., Kreysa, E., Steppe, H., Forveille, T., Omont, A., 1991, A&A 248, 555.
"CO in the southern planetary nebulae NGC 6072, NGC 6563, and IC 4406", Cox, P., Huggins, P.J., Bachiller, R., Forveille, T., 1991, A&A 250, 533.
"CO in mergers. III. NGC 1614 and NGC 3256", Casoli, F., Dupraz, C., Combes, F., Kazes, I., 1991, A&A 251, 1.
"A study of southern extreme IRAS galaxies. III. CO (J=1-0) line observations", van Driel, W., van den Broek, A.C., 1991, A&A 251, 431.
"13CO emission in the irregular galaxy NGC 55 and the IR-luminous galaxy NGC 3256", Becker, R., Freudling, W., 1991, A&A 251, 454.
"A multi-wavelength analysis of interstellar CN: comparison of red and violet absorption line observations", Gredel, R., van Dishoeck, E.F., Black, J.H., 1991, A&A 251, 625.
"Dust emission from star forming regions. I. The W49A and W51A complexes", Sievers, A.W., Mezger, P.G., Gordon, M.A., Kreysa, E., Haslam, C.G.T., Lemke, R., 1991, A&A 251, 231.
"The bipolar planetary nebula IC 4406: CO, optical and dust emission", Sahai, R., Wootten, A., Schwarz, H.E., Clegg, R.E.S., 1991, A&A 251, 560.
"CO observations of southern S0 galaxies", Tacconi, L., Tacconi-Garman, L.E., Thornley, M., van Woerden, H., 1991, A&A 252, 541.
"Dust disks around Vega-type stars", Chini, R., Krugel, E., Shustov, B., Tutukov, A., Kreysa, E., 1991, A&A 252, 220.
"The connection between the low polarization quasar 3C273 and blazars", Valtaoja, L., Valtaoja, E., Shakhovskoy N.M., Efimov Yu.S., Takalo, L.O., Sillanpaa, A., Tornikoski M., Kidger M.R., de Diego J.-A., 1991, AJ 102, 1946.

1992

"SEST CO observations of galaxies in the Grus quartet: NGC 7582 and NGC 7552", Claussen, M.J., Sahai, R., AJ 103, 1134.
"Discovery of a fast, bipolar mass-outflow from the prototype S-star pi1 Gru", Sahai, R., 1992, A&A 253, L33.
"The circumstellar envelope of the carbon star S Scuti", Olofsson, H., Carlstrom, U., Eriksson, K., Gustafsson, B., 1992, A&A 253, L17.
"Evidence for heavy element dust clumps from the increasing 1300 micrometer emission from Supernova 1987 A", Biermann, P.L., Chini, R., Haslam, C.G.T., Kreysa, E., Lemke, R., Sievers, A., 1992, A&A 255, L5.
"Carbon monoxide in active galaxies", Chini, R., Krugel, E., Steppe, H., 1992, A&A 255, 87.

"Dust emission from star forming regions. II.. The NGC 2024 cloud core - revisited", Mezger, P.G., Sievers, A.W., Haslam, C.G.T., Kreysa, E., Lemke, R., Mauersberger, R., Wilson, T.L., 1992, A&A 256, 631.
"The structure of the high-latitude molecular cloud toward HD 210121", Gredel, R., van Dishoeck, E.F., de Vries, C., Black, J.H., 1992, A&A 257, 245.
"The detection of the CO emission of the elliptical galaxy NGC 7176", Huchtmeier, W.K., Tammann, G.A., 1992, A&A 257, 455.
"Carbon monoxide emission from the planetary nebula M 3-28", Gomez, Y., Rodriguez, L.F., Garay, G., 1992, A&A 258, 469.
"Molecular abundances in the Sagittarius A molecular cloud", Minh, Y.C., Irvine, W.M., Friberg, P., 1992, A&A 258, 489.
"A survey of circumstellar CO emission from a sample of IRAS point sources", Nyman, L.-A., Booth, R.S., Carlstrom, U., Habing, H.J., Heske, A., Sahai, R., Stark, R., van der Veen, W.E.C.J., Winnberg, A., 1992, A&AS 93, 121.
"A molecular outflow associated with Herbig-Haro jet HH46/47", Olberg, M., Reipurth, B., Booth, R.S., 1992, A&A 259, 252.
"Molecular outflows associated with HH52-54 and IRAS 12496-7650", Knee, L.B.G., 1992, A&A 259, 283.
"Galaxy photometry at milimetric wavelengths", Andreani, P., Franceschini, A., 1992, A&A 260, 89.
"Anatomy of the Sagittarius A complex. II. 1300 micrometer and 870 micrometer continuum observations of Sgr A* and its subm/IR spectrum", Zylka, R., Mezger, P.G., Lesch, H., 1992, A&A 261, 119.
"Search for molecular gas in polar ring galaxies and the giant low surface brightness galaxy Malin I", Radford, S.J.E., 1992, A&A 262, 13.
"The (12CO/13CO) ratio towards zheta Ophiuchi", Wilson, T.L., Mauersberger, R., Langer, W.D., Glassgold, A.E., Wilson, R.W., 1992, A&A 262, 248.
"Carbon-bearing molecules in the envelopes around oxygen-rich stars. First detection of formaldehyde in an oxygen-rich circumstellar envelope", Lindqvist, M., Olofsson, H., Winnberg, A., Nyman, L.-A., 1992, A&A 263, 183.
"Submm/mm observations of the Monoceros R2 cloud core", Henning, Th., Chini, R., Pfau, W., 1992, A&A 263, 285.
"M1-16: multiple shocked outflows from an evolved object", Schwarz, H.E., 1992, A&A 264, L1.
"A molecular line survey of the merger NGC 3256", Casoli, F., Dupraz, C., Combes, F., 1992, A&A 264, 49.
"The case of missing 13CO in mergers", Casoli, F., Dupraz, C., Combes, F., 1992, A&A 264, 55.
"Deducing a molecular ring structure in the nucleus of NGC 4945 from CO line profiles", Bergman, P., Aalto, S., Black, J.H., Rydbeck, G., 1992, A&A 265, 403.
"Molecular-line emission from the centres of Centaurus A and other southern galaxies", Israel, F.P., 1992, A&A 265, 487.
"Dust emission from star-forming regions. III. The Rho Ophiuchus cloud - where are the low-mass protostars?", Mezger, P.M., Sievers, A., Zylka, R., Haslam, C.G.T., Kreysa, E., Lemke, R., 1992, A&A 265, 473.
"Chemistry in the molecular envelopes of the planetary nebulae NGC 6072 and IC 4406", Cox, P., Omont, A., Huggins, P.J., Bachiller, R., Forveille, T., 1992, A&A 266, 420.

"An optical/infrared/millimetre study of HH 90/91", Gredel, R., Reipurth, B., Heathcote, S., 1992, A&A 266, 439.

1993

"IRAS 06562-0337: final mass-loss episodes before the formation of a planetary nebula?", Garcia-Lario, P., Manchado, A., Sahu, K.C., Pottasch, S.R., 1993, A&A 267, L11.
"Millimetre observations of old novae", Weight, A., Evans, A., Albinson, J.S., Krautter, J., 1993, A&A 268, 294.
"Modelling of the CO emission around the carbon star S Scuti", Bergman, P., Carlstrom, U., Olofsson H., 1993, A&A 268, 685.
"Dust shell modelling of the carbon star IRAS 15194-5115", Lopez, B., Perrier, C., Mekarnia, D., Lefevre J., Gay, J., 1993, A&A 270, 462.
"The distribution of CO in NGC 4945", Dahlem, M., Golla, G., Whiteoak, J.B., Wielebinski, R., Huttemeister, S., Henkel, C., 1993, A&A 270, 29.
"Results of the ESO-SEST Key Programme: CO in the Magellanic Clouds. II. CO in the SW region of the Small Magellanic Cloud", Rubio, M., Lequeux, J., Boulanger, F., Booth, R.S., Garay, G., de Graauw, Th., Israel, F.P., Johansson, L.E.B., Kutner, M.L., Nyman, L.-A., 1993, A&A 271, 1.
"Results of the ESO-SEST Key Programme: CO in the Magellanic Clouds. III. Molecular gas in the Small Magellanic Cloud", Rubio, M., Lequeux, J., Boulanger, 1993, A&A 271, 9.
"The mass loss history of high latitude supergiants", van der Veen, W.E.C.J., Trams, N.R., Waters, L.B.F.M., 1993, A&A 269, 231.
"A molecular radio line survey of the carbon star IRAS 15194-5115", Nyman, L.-A., Olofsson, H., Johansson, L.E.B., Booth, R.S., Carlstrom, U., Wolstencroft, R., 1993, A&A 269, 377.
"High resolution CO(2-1) observations of the molecular gas in Centaurus A", Rydbeck G., Wiklind T, Cameron M., Wild W., Eckart A., Genzel R., Rothermel H., 1993, A&A 270, L13.
"CO emission from molecular gas at -190 kilometers per second near Sagittarius A", Liszt, H.S., Burton, W.B., 1993, ApJ 407, L25.
"The infrared-millimetre-centimetre flaring behaviour of the quasar 3C273", Robson, E.I., Litchfield, S.J., Gear, W.K., Hughes, D.H., Sandell, G., Courvoisier, T.J.-L., Paltani, S., Valtaoja, E., Terasranta, H., Tornikoski, M., Steppe, H., Wright, M.C.H., 1993, MNRAS 262, 249.
"A study of circumstellar envelopes around bright carbon stars. I. Structure, kinematics and mass-loss rate", Olofsson, H., Eriksson, K., Gustafsson, B., Carlstrom, U., 1993, ApJS 87, 267.
"A study of circumstellar envelopes around bright carbon stars. II. Molecular abundances", Olofsson, H., Eriksson, K., Gustafsson, B., Carlstrom, U., 1993, ApJS 87, 305.
"Cold dust around Herbig-Haro energy sources: a 1300 micrometer survey", Reipurth, B., Chini, R., Krugel, E., Kreysa, E., Sievers, 1993, A&A 273, 221.
"The molecular cloud associated with the H II region RCW 34", Pagani, L., Heydari-Malyeri, M., Castets, A., 1993, A&A 275, 573.
"Survey of a complete sample of southern extragalactic radio sources", Tornikoski, M., Valtaoja, E., Terasranta, H., Lainela, M., Bramwell, D., Botti, L.C.L., 1993, A.J., 105

(5), 1680.
"A 1.3 mm survey for circumstellar dust around young Chamaeleon objects", Henning, Th., Pfau, W., Zinnecker, H., Prusti, T., 1993, A&A 276, 129.
"Cold dust around high-redshift quasars", Andreani, P., La Franca, F., Cristiani, S., 1993, MNRAS 261, L35.
"CO(2-1) and 13CO(1-0) emission from luminous southern infrared galaxies", Garay, G., Mardones, D., Mirabel, I.F., 1993, A&A 277, 405.
"The velocity field of the outer Galaxy", Brand, J., Blitz, L., 1993, A&A 275, 67.
"Results of the ESO-SEST Key Programme on CO in the Magellanic Clouds. I.. A survey of CO in the LMC and the SMC", Israel, F.P., Johansson, L.E.B., Lequeux, J., Booth, R.S., Nyman, L.-A., Crane, P., Rubio, M., de Graauw, Th., Kutner, M.L., Gredel, R., Boulanger, F., Garay, G., Westerlund, B., 1993, A&A 276, 25.
"Large scale structure of the R Coronae Australis cloud core", Harju, J., Haikala, L.K., Mattila, K., Mauersberger, R., Booth, R.S., Nordh, H.L., 1993, A&A 278, 569.
"Dust in spiral galaxies. I.", Chini, R., Krugel, E., 1993, A&A 279, 385.
"Infrared and SiO maser observations of OH/IR stars", Nyman, L.-A., Hall, P.J., Le Bertre, T., 1993, A&A 280, 551.
"Evolution in dust lane ellipticals: detection of accreted molecular gas", Sage, L.J., Galletta, G., 1993, ApJ 419, 544.
"Anatomy of the Sagittarius complex. III. Morphology and characteristics of the Sgr B2 giant molecular cloud", Gordon, M.A., Berkermann, U, Mezger, P.G., Zylka, R., Haslam, C.G.T., Kreysa, E., Sievers, A., Lemke, R., 1993, A&A 280, 208.
"A 100 GHz map of 3C446", Lerner, M.S. et al., 1993, A&A 280, 117.

1994

"CO in paired galaxies: star formation induced by gas flow", Combes, F., Prugniel, P., Rampazzo, R., Sulentic, J.W., 1994, A&A 281, 725.
"Constraints on molecular gas in cooling flows and powerful radio galaxies", O'Dea, C., Baum, S., Maloney, P.R., Tacconi, L.J., Sparks, W.B., 1994, ApJ 422, 467.
"A search for cold dust around post - T Tauri candidates", Gahm, G.F., Zinnecker, H., Pallavicini, R., Pasquini, L., 1994, A&A 282, 123.
"A 230 GHz receiver for SEST", Bloemhof, E.E., Blundell, R., Miller, R.E., 1994, A&A 282, 318.

AGREEMENT BETWEEN NATURVETENSKAPLIGA FORSKNINGSRADET (SWEDISH NATURAL SCIENCE RESEARCH COUNCIL) AND THE EUROPEAN SOUTHERN OBSERVATORY

The Swedish Natural Science Research Council, hereinafter referred to as NFR

and

The European Organisation for Astronomical Research in the Southern Hemisphere, hereinafter referred to as ESO

have agreed as follows:

Article 1

NFR and ESO will jointly install and operate on ESO territory on La Silla a 15 m submillimetre telescope which will be referred to by the acronym SEST (Swedish-ESO Submillimetre Telescope) for a period of fifteen years from the date of the signing of this agreement.

Article 2

The capital cost of the SEST (complete telescope + building), estimated as DM 8.600.000 (1983) shall be borne by NFR and ESO as follows:

NFR : DM 3.000.000
ESO : DM 5.600.000

These contributions will be subject to adjustment due to the cost variation specified in the telescope contract with IRAM (Appendix I), and for other items to the approved ESO cost variation. In addition, the two parties will each make available DM 500.000 for the initial receivers.

Article 3

Further organisational and budgetary arrangements not covered in this agreement shall be agreed upon between NFR and ESO in an exchange of letters.

Article 4

The erection of the telescope will take place at La Silla on a site fixed by mutual agreement.

Article 5

The telescope will be a 15 m IRAM telescope as defined in the contract with IRAM. Its specifications shall be agreed upon between NFR and ESO in an exchange of letters. To the extent that the contract with IRAM does not specify a specific IRAM responsibility, the technical responsibility for the telescope during the construction and installation phase will be undertaken by NFR. The technical responsibility for the transport arrangements from Europe to La Silla will be undertaken by ESO.

The design of the building will be fixed by mutual agreement. Its execution will be the responsibility of ESO.

Article 6

The design and construction of the initial receivers for the telescope will be the responsibility of NFR, but the costs will be borne equally by the two parties within the budgetary framework specified in Art. 2.

These receivers will be specified in an exchange of letters between NFR and ESO. Additional receivers may be provided later by the two parties under conditions to be mutually agreed upon.

Article 7

Any alterations to the telescope, the receivers, or the building as specified in Art. 2, 4 and 5 shall be made by mutual agreement.

Article 8

The telescope, the building and the auxiliary equipment, furniture, measuring instruments, etc. remain the property of NFR and ESO in relation to their respective investments for these items.

The parties may agree to insure the properties in which case the cost shall be shared in the same proportion.

Article 9

ESO shall undertake to provide those utilities necessary for basic functioning of the telescope and initial receivers, e.g. water, electricity, heating, liquid helium, etc. However, when during the time allotted to NFR special receivers are installed which have a much larger consumption of utilities than the receivers available as standard observatory instrumentation, ESO may charge NFR for this.

Article 10

NFR will provide a team of five persons full time, including the Scientist in charge of the telescope. NFR and ESO shall establish the necessary arrangements for the payment of salaries and site supplements to these persons, but the cost will be borne by NFR.

ESO will provide a team of three persons full time and support personnel in mechanics, digital electronics, etc., equivalent to one person full time.

ESO or NFR may request on the basis of duly justified reasons the replacement of a staff member provided to the project by the other organisation. Such a request would be jointly discussed before a final decision.

Article 11

ESO has the responsibility for the maintenance of the building, the day-to-day maintenance of the telescope and associated computer, and shall bear the corresponding costs.

Article 12

The maintenance of the receivers mentioned under Art. 5 shall be the responsibility of NFR. The costs of replacement parts and of NFR personnel beyond that mentioned under Art. 9 shall be shared between ESO and NFR in proportion to their annual share of the observing time.

Article 13

The costs of accidental damage to the telescope associated with the operation shall be borne by ESO and NFR in proportion to their annual share in the observing time.

Article 14

Individual observers may provide and install their own receivers, subject to the agreement of NFR and ESO.

Article 15

All observers and personnel shall be subject to the internal rules of ESO. They will receive transport in Chile, board and lodging on the ESO premises on terms and conditions agreed upon by NFR and ESO.

Article 16

ESO will have the right to 50% of the observing time and NFR to 50%, which latter figure then also includes what otherwise would have been the Swedish share of the ESO time, so far as possible evenly distributed over the seasons. Decisions with regard to this distribution shall be taken in mutual agreement.

Article 17

NFR will inform ESO about its observing programmes and observers in due time. Possible conflicts in this area will be resolved by mutual agreement.

NFR, in agreement with the Director General of ESO, may invite observers and personnel of other countries to share its observing time. Such observers and personnel shall have the same rights and obligations as observers and personnel of NFR.

Article 18

Two years before the termination of this agreement, NFR and ESO shall discuss its prolongation.

Article 19

Should essential circumstances and conditions underlying this agreement change or cease, both parties will enter into negotiations with respect to a revision of this agreement, fully or part.

Article 20

In case of termination of the agreement, ESO and NFR will decide about the disposition of the telescope, the receivers and the building in mutual agreement.

Article 21

All and any dispute which could arise between ESO and NFR out of or in connection with the interpretation or application of the present agreement and which could not be settled by way of direct negotiations will, unless the parties agree on another method of settlement, be submitted at the request of one of them to a Court of Arbitration consisting of three members, i.e. one arbiter appointed by ESO, one arbiter appointed by NFR, and a third one elected unanimously by the two others who cannot be an official of the Organisation nor a Swedish subject and who will chair the Court.

The application to institute arbitral proceedings must contain the name of the arbiter appointed by the plaintiff's party; the defendant's party will have to appoint its arbiter and communicate his name to the other party within two months from the date of receipt of the application to institute arbitral proceedings. Should the defendant's party not notify the name of its arbiter within the above mentioned period, or should the two arbiters not agree upon the election of a third arbiter within two months from the last arbiter designation, the arbiter or the third arbiter, according to the case, will be appointed by the President of the International Court of Justice upon request of the most diligent party.

The Court of Arbitration shall convene in Munich and decide on the basis of the terms of the present contract and subsidiarily the terms of German law. The tribunal will establish the rules of procedure. Its decisions will be imposed upon the parties and are incontestable.

In witness whereof the undersigned have signed this Agreement.

Onsala, 26 June 1984

For the Swedish Natural Science Research Council

Professor I. LINDQVIST

Huvudsekreterare, NFR

For the European Organisation for Astronomical Research in the Southern Hemisphere

On behalf of:

Professor L. WOLTJER

Director General of ESO

The European Organisation for Astronomical Research in the Southern Hemisphere, hereinafter referred to as ESO

and

The Institut de Radio Astronomie Millimétrique, hereinafter referred to as IRAM

taking note of the interest of ESO to jointly with the Swedish Natural Science Research Council install a 15 m telescope for mm observations at La Silla,

and taking note of the intent of IRAM to construct several such telescopes,

have agreed as follows:

Article 1

IRAM will include one additional telescope (without control computer, transporter and pedestal) for ESO in the existing manufacturing contracts for the three IRAM 15 m interferometer telescopes, provided the cost does not exceed FF 18.000.000 (Jan. 1, 1984, augmented with cost variation as under Art. 2).

Article 2

ESO will reimburse to IRAM the cost of the telescope augmented with one quarter of the expenses for tooling, quality control and acceptance testing for the four telescopes. The cost variation to be applied will be in accordance with the cost variation clauses in the contracts between IRAM and the firms manufacturing the telescopes.

In addition, ESO will pay to IRAM a sum of FF 1.000.000 as its share in the external contracts which IRAM has placed during the development phase.

Article 3

IRAM will pass on to ESO the guarantees given by the manufacturing firms. In case claims have to be made against the firms, IRAM undertakes to do so, while ESO will reimburse IRAM for the corresponding costs.

Article 4

IRAM will provide the same care in supervising the contractors during manufacturing and testing of the telescope at the manufacturer as applied to the interferometer telescopes. ESO will assume the responsibility for the transport of the telescope to La Silla.

IRAM will assist ESO in the assembly and installation of the telescope at La Silla. ESO will pay the travel costs and the salary cost of the necessary IRAM personnel.

The detailed arrangements will be dealt with in an exchange of letters between IRAM and ESO.

Article 5

IRAM will provide ESO with all applicable software for the telescope control. In case a different computer is used by ESO, it will be ESO's responsibility to make the necessary alterations in the software.

Article 6

Upon completion of the telescope installation at La Silla, a joint acceptance test will be made by IRAM and ESO, which will be followed by a joint acceptance protocol.

Article 7

All and any dispute which could arise between ESO and IRAM out of or in connection with the interpretation or application of the present agreement and which could not be settled by way of direct negotiations will, unless the parties agree on another method of settlement, be submitted at the request of one of them to the Court of Arbitration consisting of three members, i.e. one arbiter appointed by ESO, one arbiter appointed by IRAM , and a third one elected unanimously by the two others who cannot be an official of either Organization and who will chair the Court.

The application to institute arbitral proceedings must contain the name of the arbiter appointed by the plaintiff's party; the defendant's party will have to appoint its arbiter and communicate his name to the other party within two months from the date of receipt of the application to institute arbitral proceedings. Should the defendant's party not notify the name of its arbiter within the above mentioned period, or should the two arbiters not agree upon the election of a third arbiter within two months from the last arbiter designation, the arbiter or the third arbiter, according to the case, will be appointed by the President of the International Court of Justice upon request of the most diligent party.

The Court of Arbitration shall convene in Munich and decide on the basis of the terms of the present contract and subsidiarily the terms of German law. The tribunal will establish the rules of procedure. Its decisions will be imposed upon the parties and are incontestable.

In witness whereof the undersigned have signed this Agreement.

Onsala, 26 June 1984

For the European Organisation
for Astronomical Research in
the Southern Hemisphere

On behalf of:

Professor L. WOLTJER

Director General of ESO

For the Institut de Radio
Astronomie Millimétrique

Dr M.J. DE JONGE

Director of IRAM

Agreement between NFR and CTH on the construction and operation of the Swedish-ESO Submillimetre Telescope (SEST)

Considering the agreement between NFR and ESO (dated 26 June 1984) to jointly install and operate a submillimetre telescope, a project referred to by the acronym SEST, and further considering the important part which Onsala Space Observatory of CTH has to play in this project, NFR and CTH agree:

General provisions

1. that on behalf of NFR the project will be led by the Director of Research of Onsala Space Observatory Professor R.S. Booth. It will be his responsibility to represent NFR in the direction, installation and operation of the telescope and its instrumentation. In relation to the agreement between NFR and ESO, this means that Professor Booth is authorized to represent NFR in all matters coming under articles 4, 5, 6, 12, 14 and 15 of the said agreement.

Staff (Article 10)

2. that Onsala Space Observatory/Elektronfysik I shall, within present funding arrangements, make available to the project one engineer (based at Onsala) and one senior research student or research assistant.

3. that NFR shall provide three positions to the project, namely the site scientist and two site engineers all of whom shall be directly responsible to the project leader.

Fiancial management

4. that NFR shall seek to establish (in an exchange of letters with ESO as foreseen in Article 3 of the agreement between NFR and ESO) budgetary arrangements in which the project leader normally be given authority to execute budgets and draw on the funds put at the project's disposal by NFR and/or ESO.

Negotiations to change this agreement may be requested by either party at any time.

For naturvetenskapliga forskningsrådet		For Chalmers tekniska högskola	
12. FEB. 1985	*[signature]*	Febr. 13, 1985	*[signature]*
Date	Ingvar Lindqvist	Date	Sven Olving

I agree to the terms of this Agreement and accept the responsibilities it confers upon me

15 Feb. 1985	*[signature]*
Date	Roy Booth

Agreement concerning the operation of SEST (Swedish-ESO Submillimetre Telescope)

Whereas an agreement for the installation and operation of SEST was signed on 26 June 1984 between the Swedish Natural Science Research Council (NFR) and the European

Whereas an agreement was signed on 12 and 13 February 1985 between NFR and the Chalmers University of Technology (CTH) in which NFR delegated important responsibilities for its part of SEST project to the Onsala Space Observatory (OSO) of the CTH,

Whereas SEST has been successfully installed and is operating with scheduled observations since April 1988,

Whereas on 24 January 1990, OSO became a National Facility with direct Government funding channelled through CTH,

Considering the role to be played by OSO of the CTH in the future operation of SEST,

NFR, ESO and CTH have agreed as follows:

Article 1

CTH will take over, from 1 July 1990, all the obligations entered into by NFR in the above mentioned agreement between NFR and ESO. It is understood that the transfer of the contractual responsibility for the Swedish part of SEST from NFR to CTH does not preclude future NFR support to SEST when so deemed necessary.

Article 2

The organisational and budgetary arrangements agreed upon by NFR and ESO in an exchange of letters dated 6 May 1986 and 10 July 1986, respectively, shall continue to apply with CTH taking over the role of NFR from 1 July 1990.

Article 3

NFR and CTH conclude this agreement subject to approval by the Swedish Government.

For the Swedish Natural Science Research Council

Professor Carl Nordling

Dr. Mats Ola Ottosson

For the Chalmers University of Technology

Professor Anders Sjöberg
Rektor

Dr. Folke Hjalmers
Registrar

Dr. Sten Gustavsson
Chairman, OSO Board

Professor Roy S. Booth
Director, OSO

For the European Southern Observatory

Professor Harry van der Laan
Director General