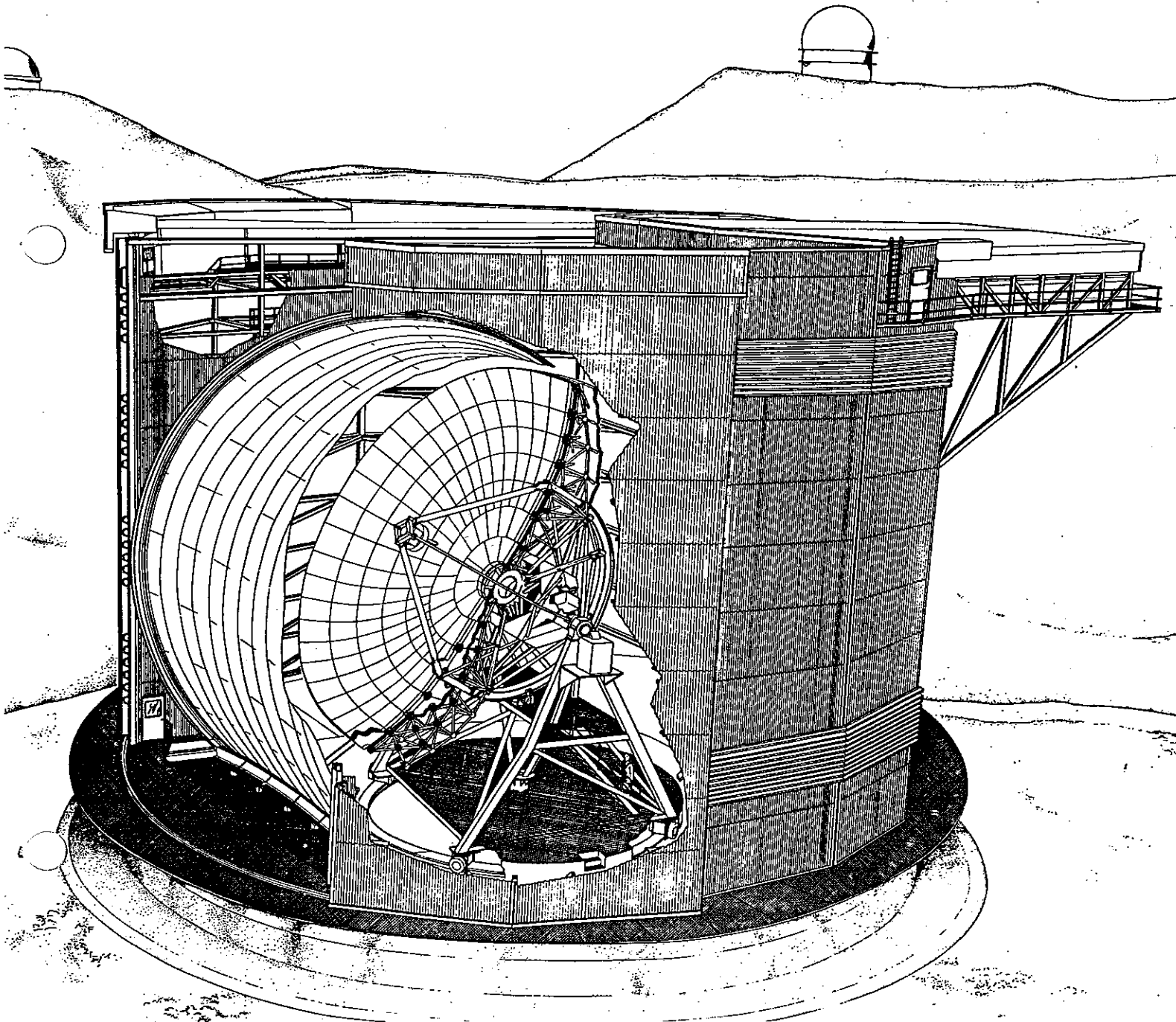
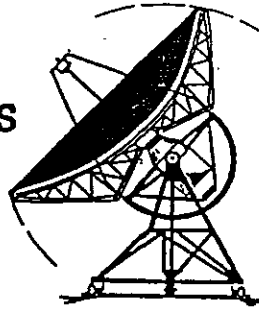


# PROTO STAR

The NEWSLETTER of the  
UNITED KINGDOM - NETHERLANDS  
MILLIMETRE-WAVE TELESCOPE

Number 1

October 1984



The United Kingdom-Netherlands Millimetre-wave Telescope Project is now well under way and the time is ripe for the inauguration of a newsletter. This first issue is intended for the widest possible audience because the telescope will be capable of making important contributions to many diverse fields of research and will in consequence be used by many astronomers who have not yet made observations in the millimetre and submillimetre wavebands. Many potential users are therefore unlikely to be familiar with the plans so this issue of The Protostar is devoted not to the usual miscellany of news items one might expect of a newsletter but to a fairly extensive summary of the design of the telescope and the receivers, of the state of the project and of the various types of astronomy to which the telescope is applicable.

It is anticipated that The Protostar will be published twice yearly. The circulation will not ordinarily be as wide as for this issue so, if you wish to receive the newsletter in future and are not on the standard PATT circulation list, please fill in and return the slip at the end of this copy.

#### THE SPECIFICATIONS OF THE TELESCOPE

The telescope is to be capable of making total intensity measurements both of spectral lines (with a resolution of order  $10^5$  to  $10^7$ ) and of the continuum (resolution  $10^{-3}$  to 0.3). In addition, the telescope will be capable of polarimetry and of interferometry when linked either to nearby or to distant telescopes. The possible modes of observation will be numerous and will range from long integration on weak sources to rapid mapping of extended objects.

The telescope will be a folded Cassegrain on an altazimuth mount, and will be situated inside a rotating enclosure known as the carousel. The diameter of the primary mirror will be 15 m and the secondary mirror, which will be capable of chopping, will be 75 cm in diameter. The telescope will be usable over the wavelength range from 0.3 to 13 mm and optimised for 0.8 to 4.0 mm. Several receivers will be mounted on the telescope simultaneously and, to make optimum use of the seeing conditions, it will be possible to switch from one receiver to another in a time of only a few minutes. Provision is also being made to allow for the use of multifrequency and multibeam receivers. The

field of view will be 6 arcmin in diameter and the instrumental polarisation less than 2%.

The ratio of the actual antenna gain to that expected for an ideal antenna of the same diameter and illumination pattern will be greater than the values in the following table, in which are given the efficiency factors for the three causes of loss, together with their product:

$\lambda/\text{mm}$	0.4	0.6	0.8	1	2
Ohmic loss (membrane, surface and gaps)	0.8	0.84	0.88	0.92	0.95
Wide-angle scattering (blocking)	0.8	0.8	0.8	0.8	0.8
Path length errors	0.08	0.33	0.54	0.67	0.91
Combined efficiency	0.05	0.22	0.38	0.49	0.69

The range of elevation available for observations will be from 5° to 80°, and all azimuths will be available. The absolute or blind pointing accuracy will be better than 5 arcsec rms in each coordinate, and the errors when tracking a source for up to one hour or when moving from a reference source within 30° on the sky will be less than 2 arcsec rms. The planned maximum speeds and accelerations are 1.5 deg/s and 0.3 deg/s<sup>2</sup>, and the dynamical performance should be such as to allow the following typical rates: from source to source 30° away in 30s; from source to reference 2° away in 10s; to map 100 points in a 6 x 6 arcmin<sup>2</sup> source in 2 min; to beamswitch with a 6 arcmin throw at 1 Hz or with a 30 arcsec throw at 5 Hz.

The path length errors are clearly a critical feature of the performance. The main contributions and their rms allowances to the wavefront distortion (in units of  $\mu\text{m}$ ) are as follows: the surface panels, 30; the panel mounts, 14; the backing structure, 25; the secondary mirror, 14; the transparent membrane across the open slit of the carousel, 10; measurement inaccuracy 10 and misalignment 10. The root sum of squares of the above is 50 $\mu\text{m}$  and the

contribution to the telescope efficiency given earlier was calculated from this figure and the Ruze formula. It will be some time before firm experimental or calculated values will be available for all these factors but there have been several encouraging results lately, particularly in the design of the backing structure and in the replication of the panels, which suggest that the final accuracy may turn out to be considerably better than the above figures suggest.

All the figures given so far in this section are specifications, that is values which the design should meet with a high degree of confidence. There are in addition a number of design goals, values which the designers will be aiming for. The goals are more stringent than the corresponding specifications; for example, the design goals for the absolute and tracking pointing accuracies are 3 and 1 arcsec rms respectively. The specifications also apply to the worst case of observing conditions such as 80 km/hr wind gusts, temperature anywhere in the range from -10 to +20°C and changing at a rate of 5°C/hr, and with the elevation anywhere in the full range of angles from 5 to 80 degrees. In a benign set of conditions (on a calm night and with a limited elevation range) the combined error allowance changes from 50 to 40µm rms so it seems reasonable to adopt a goal of 35µm rms under these conditions. If this can be met, the bottom line of the table for aperture efficiency will read:

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$\lambda/\text{mm}$	0.4	0.6	0.8	1	2
Combined efficiency	0.19	0.39	0.52	0.61	0.72

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### THE SITE

One of the major decisions in the history of the project was to site the telescope at the summit of Mauna Kea on the Big Island of Hawaii rather than on the Roque de los Muchachos on the island of La Palma in the Canaries. An agreement has been reached with the University of Hawaii to build the telescope on the new site and construction began in Spring 1983, which will enable completion by late 1986 in accordance with the Astronomy, Space and Radio Board's provision in the current Forward Look.

The Project Team at the Rutherford Appleton Laboratory produced a new design which is optimised for the Hawaiian site. It maintains the full scientific specification of the telescope while costing no more than the old design. The new site is ideal for the telescope because the performance of both is exceptionally good at short millimetre wavelengths. The atmospheric opacity at these wavelengths is determined principally by the water vapour content and, because of the greater altitude, Mauna Kea is considerably drier than La Palma. The difference between the sites is particularly great at the shortest wavelengths (0.3 - 0.7 mm) where the atmospheric attenuation is very strong; the transmission is usable for about one third of the time on Mauna Kea whereas only occasional observing opportunities are likely on La Palma. For the band between 0.7 and 1 mm, where the telescope is designed to have its best performance, Mauna Kea offers a substantial advantage in terms both of the number of usable days and of the average transmission of the atmosphere on those days. At wavelengths longer than 1 mm the attenuation is relatively small and there is less advantage in the short term, but as receivers improve the sensitivity may ultimately be limited by the noise from atmospheric emission and the advantage of the drier site will again become significant.

The telescope will be run by the Royal Observatory, Edinburgh, in parallel with the United Kingdom Infrared Telescope (UKIRT). This arrangement is expected to be advantageous in a number of ways. First, the management and logistics of the two telescopes have many components in common and running them in tandem will increase the efficiency. Second, the programmes of the telescopes have many scientific and technical features in common and both will benefit from being operated by a single team; already, millimetre receivers and techniques are being developed and used on the UKIRT. Both the receivers and the techniques may be used on the MT. Third, the opportunity may arise of making interferometric observations between the MT and the the Cal Tech 10 m diameter millimetre and submillimetre-wave telescope; there are considerable technical difficulties but an angular resolution of about one arc second is potentially available for measurements of size and position. Fourth, the UKIRT has recently been controlled and operated directly from Edinburgh, so by the time the MT comes into operation it should be possible to observe with both telescopes by remote control, with a saving in travel time, manpower and costs.

## RECEIVERS

It is planned to have a range of common-user receivers operating when the telescope is commissioned. There are financial limits on what is possible, and a meeting of the Users' Committee was given over to finding out which frequency bands were thought by astronomers to have the highest priority, given the likely performance of the dish and the site. Broad agreement emerged that the band from 330 to 365 GHz was preferred over all others, with the bands from 190 to 310 and from 455 GHz on up in second place.

As for the technology which will be implemented, the Project is supporting a wide range of research and development work so that appropriate choices may be made. The Receiver Working Group is sponsoring work on receiver research and development which covers a great range of techniques. For front-end receivers, Schottky, InSb, Superconductor-Insulator-Superconductor, Josephson Junction and bolometer systems are all under development, some of them with multiple-beam capability. Quasi-optical, local oscillator and intermediate frequency work is also being supported, and acousto-optical and digital back-end spectrometers are under study.

## THE STATE OF THE PROJECT

The project is now well under way. The foundations of the telescope and carousel are in place, having been built in the summer season of 1983 by Riersons, a Hawaiian firm of contractors. The carousel was also constructed in 1983 and trial-erected in November in the yard of the manufacturer, Robert Watsons of Bolton. Tests proved satisfactory so it was dismantled and loaded onto a boat which arrived in Hilo in May 1984 after an unexpectedly eventful voyage; it is being reassembled on the Mauna Kea site and is now almost complete. The contract for the steelwork of the antenna has been put out to the Dutch firm Genius of IJmuiden and the work will be complete in time for shipping to Mauna Kea in July 1985. The reflecting panels of the dish are in production at Rutherford Appleton Laboratory and one third have been completed. Finally, the types of receiver which will be built first and the groups which will build them were decided at a meeting of the Receiver Working Group in June 1984, and construction will begin soon.

FINANCES

The financial provisions made for the construction phase of the project are as follows:

1984/85	1985/86	1986/87	1987/88
£3,098k	£2,651k	£1,000k	£179k

The figures are quoted at October 1983 prices and with US Dollar expenditure related to Sterling at a rate of \$1.50/£1. The provisions are adequate to allow the construction phase to be completed on schedule by mid 1986, when the commissioning phase will commence.

THE MILLIMETRE-WAVE TELESCOPE USERS' COMMITTEE

The MT Users' Committee was set up to give advice to the SERC on the scientific development and exploitation of the telescope. It is the principal channel of communication between the telescope users and the project, and potential users may find it of value to know who the present members of the committee are:

- Professor R.D. Davies, (Chairman), Manchester
- Professor A. Hewish, Cambridge
- Dr R.E. Hills (Project Scientist), Cambridge
- Dr P.A.R. Ade, Queen Mary College
- Dr B. Baud, Laboratorium voor Ruimteonderzoek
- Dr J.M. Brown, Oxford
- Dr A.M. Flett, Aberdeen
- Dr F.P. Israel, ESTEC, Noordwijk
- Dr R.D. Joseph, Imperial College
- Dr L.T. Little, Kent
- Dr E.I. Robson, Preston Polytechnic
- Dr G. White, Queen Mary College
- Dr D. Williams, UMIST

## MILLIMETRE ASTRONOMY ON THE UKIRT

The UKIRT has already been used for a variety of observations at short millimetre and submillimetre wavelengths, and proposals to PATT for such observations currently represent about 30% of all UKIRT proposals. There is at the moment only one instrument which belongs permanently at the UKIRT: this is the device known affectionately as "The Coffin" which can be operated either as a broadband Schottky mixer receiver in the 230 GHz band or as an InSb heterodyne bolometer in the 350 GHz band. It makes use of the back-end digital spectrometer made at the University of Kent which also resides permanently on Mauna Kea. Other receivers which have been used at the UKIRT include various Schottky mixers and InSb heterodyne bolometers, and also broad-band direct bolometers. In the near future, a broadband Schottky mixer receiver will be commissioned as a common-user instrument by a Dutch group led by Dr Th. de Graauw, and it is also planned to have a common-user bolometer soon. The Cambridge group are also commissioning a Schottky receiver.

## THE SIGNIFICANCE OF OBSERVATIONS IN THE MILLIMETRE AND SUBMILLI-METRE WAVEBANDS

### 1. INTRODUCTION

The millimetre and submillimetre wavebands offer the astronomer, physicist and chemist unique opportunities for studying some of the most pressing problems in contemporary astrophysics. The principal observables are the spectral lines of molecules and atoms, the thermal continuum emission of warm dust grains, the bremsstrahlung of hot gas and the synchrotron radiation of high energy electrons in gravitationally-collapsed objects. Thus, the range of astrophysical topics which can be studied is very broad and many of them are unique to these wavebands. The present design of the Millimetre-wave Telescope for Mauna Kea is such as to provide the most powerful observing facility in the world for all types of astronomy in the band from about 2 mm to 0.3 mm wavelength.



Here we summarise the nature of the emission mechanisms at these wavelengths and why they can yield new insights into a wide range of different astronomical problems. We then describe some of the most exciting scientific programmes which will make fundamental new contributions to our understanding of stellar and galactic evolution, of active galactic nuclei and of cosmology.

## 2. MILLIMETRE AND SUBMILLIMETRE ATOMIC AND MOLECULAR LINES

It is remarkable that molecules can exist at all in interstellar space but it is now understood that the reason that they are not destroyed by hard ultraviolet photons is that they are shielded by interstellar dust and by the molecules themselves. We also know that a large fraction of the interstellar gas in our Galaxy is in molecular form, in particular much of the gas close to the Galactic centre. The molecular gas is observed to form giant complexes of clouds with structure on many scales. It is also seen around evolved stars where dust and the molecules themselves are formed.

The reasons why millimetre and submillimetre molecular-line astronomy have such great potential are as follows:

- (a) For molecules to survive, the regions must be cool and hence the lines are very narrow. This enables accurate velocities ( $v \sim 1 \text{ km s}^{-1}$ ) within complex regions to be studied.
- (b) Many of the most important transitions are rotational transitions and have well-understood energy level diagrams. For example in carbon monoxide, CO, the  $J = 1 \rightarrow 0$  transition is at 2.6 mm,  $J = 2 \rightarrow 1$  at 1.3 mm,  $J = 3 \rightarrow 2$  at 0.86 mm,  $J = 4 \rightarrow 3$  at 0.65 mm and so on. Similar energy level diagrams with many accessible lines are present in other molecules. Thus, by studying a region in several lines of different excitations in the same molecular species it is possible to determine in an unambiguous manner temperatures and densities and, from the study of different molecules, the abundances of different molecular species.
- (c) Because the energy levels are determined by the moment of inertia of the molecules and because the lines are very narrow, isotopes of different species are readily distinguished. For example it is important to the

able to study  $^{13}\text{C}^{16}\text{O}$  and  $^{12}\text{C}^{18}\text{O}$  as well as the more abundant  $^{12}\text{C}^{16}\text{O}$  because in dense regions the molecular line emission of the latter can be highly saturated. In addition, studies of the isotopic abundances of different elements in different regions of our own and other galaxies are relatively straightforward. The rates of production of various isotopes are central for understanding the processes of formation of the heavy elements. An example of particular importance for the evolution of galaxies is the study of deuterium combined in molecules such as DCN. Deuterium is one of the elements now believed to be synthesised in the hot big bang and, because of its fragility, its persistence in the Galaxy means that not all the primordial material has been processed through stars. In fact its presence in the Galactic centre region, where star formation is currently taking place, may require the continuous infall of unprocessed material into our Galaxy from intergalactic space. Such observations are of great importance for studies of the dynamical and chemical evolution of galaxies.

- (d) The high transitions of molecules such as CO require high particle densities and temperatures to excite them, so the study of the high transitions enables studies of the physical conditions within the densest regions of the molecular clouds. Furthermore, these lines have relatively higher transition probabilities and much smaller amounts of hot gas in the innermost regions of the clouds are detectable.
- (e) In addition to these "thermal" emission processes, some of the molecular species such as OH,  $\text{H}_2\text{O}$ , and SiO have been observed to emit very high intensity lines due to maser-action. The observations of these lines provide evidence for regions of very high density,  $N(\text{H}_2) \sim 10^{7-10} \text{cm}^{-3}$ . This phenomenon is often associated with high velocity flows whose widths may be as great as  $100 \text{ km s}^{-1}$  and which are indicative of the very energetic conditions in these regions.

Thus by making detailed studies of a particular region in a number of different lines of different excitation it is possible to determine the temperature and density, the kinematics and the chemical abundances within the gas.

There are many problems which can only be studied using these millimetre and submillimetre techniques.

(a) Regions of star formation An understanding of the process of star formation is crucial to many of the most critical questions in galactic astrophysics and in the origin and evolution of galaxies. We do not know what determines the rate of star formation or how it depends on the chemical abundance of the elements, on the particle density and on the temperature. Nor do we know what determines the mass spectrum of stars. What we do know is that stars form from condensations within molecular clouds and that millimetre wave observations provide a unique tool for probing the dynamical evolution of those regions which are now undergoing star formation. Such regions are obscured optically by huge column densities of interstellar dust and the regions are too cool during the accessible phases of collapse of the protostellar region to be observable at infrared wavelengths. By using the high spatial and velocity resolution of millimetre wave observations, it is possible to distinguish between regions which are expanding or collapsing and to determine the turbulent velocities in regions of active star formation. Of special importance is the possibility of studying these regions at the highest frequencies so that one is probing as far as possible down the track of collapse which leads to star formation.

(b) The dynamics and chemical abundance of the elements in galaxies Studies of nearby galaxies are of particular importance because they give a global view of where the giant molecular clouds are located and of how they are related to different stellar populations. One also obtains directly a detailed map of the velocity field of the galaxy at very high resolution, both in velocity and in space. These studies are complementary to those made in the neutral hydrogen line, which represents only the atomic component and gives no information about molecular species, chemical abundances or detailed excitation conditions. In general, the role of neutral hydrogen is different from that of the molecular component in the evolution of galaxies.

Measurements of variations across galaxies of the relative abundance of the elements are crucial in studying the physical processes which lead to the present structures of the galaxies, and these can be carried out very effectively by mapping galaxies in different molecular species. As mentioned above, isotopic abundances are specially important in identifying the mechanisms of formation of the heavy elements and in studying the presence of primordial material in galaxies.

(c) Mass loss from stars The shells ejected by stars at the end of their lifetimes are strong sources of millimetre and submillimetre line emission. In a number of cases it is believed that dust grains are formed in the ejecta of late-type stars and that these are the sites of molecule production. Around these stars, it is possible to study the chemical processes involved in the formation of molecules and dust.

(d) The Centre of our Galaxy The central regions of our Galaxy are particularly rich in molecular species and there are many active regions of star formation close to the nucleus. Besides the obvious astrophysical importance of understanding star formation in galactic nuclei, the study of molecular species offers unique opportunities for studying the velocity field of gas close to the Galactic nucleus. From these studies, it is possible to obtain information about the gravitational potential distribution close to the nucleus and hence to discover whether there is a massive black hole at the nucleus itself. Moreover, molecular line studies can indicate whether or not material is being expelled from the nucleus and whether or not there is material falling in which could fuel a black hole at the Galactic Centre. Because of the high resolution of the millimetre wave telescope, similar studies will be possible in nearby galaxies.

(e) Interstellar Chemistry With the discovery of the vast range of molecular species present in the interstellar medium, the new field of interstellar chemistry is making major contributions to our understanding of the processes of formation and destruction of molecules. From the astronomical point of view, it is crucial to identify the mechanisms by which molecules are formed; the main theories involve either catalysis on the surface of dust grains or ion-molecule reactions in the gas phase. Molecular synthesis in stellar envelopes is also being invoked as a source of molecules. The chemical origin of these species is intrinsically bound up with the formation of molecular clouds, of interstellar grains and of protostellar objects themselves.

In turn, chemists have the opportunity to study molecules, radicals and ions in the interstellar medium which are unknown in the laboratory.  $\text{HC}_9\text{N}$ ,  $\text{C}_3\text{N}$ ,  $\text{C}_4\text{H}$ ,  $\text{HCO}^+$  and  $\text{HN}_2^+$  were all first discovered in space, and many others such as  $\text{CH}_2\text{CN}$ ,  $\text{C}_2\text{N}$ ,  $\text{HOCO}^+$ ,  $\text{H}_3\text{CO}^+$  and  $\text{H}_2\text{CN}^+$  may soon follow suit. These astronomical discoveries have been important in opening up a new area of

research into the reactions which can occur at the low temperatures and densities of interstellar space and which had not previously been considered important.

Much of the chemistry is devoted to the interactions of simple species. A good example of the type of observation central to these studies is the recent discovery of the neutral carbon line at 490 GHz (0.61mm), which has revealed that atomic carbon is surprisingly abundant in the molecular clouds. Other simple molecular species such as the metal hydrides have yet to be discovered but they are certain to be important for interstellar chemistry and have transitions accessible in the millimetre and submillimetre wavebands.

### 3. CONTINUUM OBSERVATIONS

#### 3.1. Dust around protostars and in regions of star formation

It has long been known that dust plays an essential role in the evolution of regions of star formation. Its most significant function is to act as a "transformer" in that optical and ultraviolet radiation is re-radiated as black-body radiation at the temperature to which the dust grains are heated by the incident radiation. Thus, protostars and regions where protostars are forming are characterised by intense radiation with roughly a black-body spectrum at a radiation temperature of  $\sim 30-300\text{K}$ . The regions are consequently strong submillimetre sources and their spectra rise roughly as  $\nu^3$  at wavelengths around 1mm. The identification of these regions and the determination of their spectra are among the most important projects for the millimetre wave telescope. The study of the dust in conjunction with line observations of the same regions will provide a complete thermal and dynamical model for regions of star formation. Because the spectra of these regions rise steeply there is every advantage in searching for them at the highest frequencies possible.

#### 3.2. Dust around late-type stars

Another recent discovery of importance in understanding the circulation of processed material from stars to the interstellar medium has been the discovery of continuum thermal dust emission at 0.35mm wavelength from evolved stars. These are stars which are losing material from the outer layers, which is one of the dominant processes by which gas is recirculated through the interstellar medium. The detection of dust emission from the ejected gas enables improved mass-loss rates to be determined. This discovery brings the study

of ordinary stars within the purview of the scientific programme of the millimetre wave telescope, which will have the capability of studying mass-loss from many hundreds of stars.

### 3.3 Synchrotron radiation from compact radio sources

The variability of compact radio sources of synchrotron radiation increases with increasing frequency so that at millimetre wavelengths variations on the time scale of days have been observed. According to general theoretical considerations, the variable radio source events observed in the centimetre waveband originate as events at shorter wavelengths. The systematic monitoring of active galaxies, quasars and BL Lac objects at millimetre and submillimetre wavelengths provides opportunities for probing active galactic nuclei on very compact scales, close to the ultimate energy sources themselves which almost certainly contain massive collapsed objects such as black holes. The correlation of events at these very short wavelengths with the dynamical behaviour of superluminal radio sources at centimetre wavelengths and with the non-thermal properties of sources of optical and X-ray radiation will provide insight into the origin of activity in active nuclei.

### 3.4 The Microwave Background Radiation

The microwave background radiation is the cool remnant of the hot early phase of the Universe and the peak of its Planckian spectrum lies at about 1mm wavelength. The background radiation is readily detectable at millimetre and submillimetre wavelengths. There are several observations of cosmological importance which will be possible under the very best observing conditions which concern fluctuations in the spatial distribution of the radiation and in its spectrum. The most important sources of these perturbations are Compton scattering of the background radiation by the hot gas in clusters of galaxies and those induced by the collapse of protogalaxies and protoclusters at large redshifts. The characteristic of the fluctuations is that they should be of opposite sign on either side of the maximum of the black-body spectrum. If the spectrum of the microwave background deviates significantly from Planckian form, these effects will be of particular significance in understanding the origin of the spectrum.

3.5 Solar System Observations

All the planets, their satellites, comets and asteroids are strong sources of millimetre and submillimetre radiation. Observations of the lower atmosphere of the Sun will be possible and provide estimates of particle densities in regions where other techniques of measurement are insensitive.

4. CONCLUSION

In describing the scientific programme of the millimetre wave telescope, we have concentrated upon the "bread and butter" of the project and it can be appreciated how distinctive and broad-based the scientific capabilities are. We should not neglect, of course, the potential for new discoveries in the millimetre and submillimetre wavebands; these spectral regions are still at a very early stage in their scientific exploitation. The scientific programmes are complementary to studies which can be undertaken in other wavebands. Perhaps the closest relations are with the interests of infrared astronomers. The proximity of the UK Infrared Telescope on Mauna Kea and the fact that the two telescopes will be run as a single operation provide UK and Netherlands astronomers with another unique advantage over other astronomers.

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