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# MULLARD RADIO ASTRONOMY OBSERVATORY, CAVENDISH LABORATORY, UNIVERSITY OF CAMBRIDGE

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## 1 INTRODUCTION

Observational and theoretical research has been carried out on radio galaxies and cosmology, supernova remnants, molecular clouds, the galactic centre and the heliosphere. Instruments in use at MRAO include the 5-km telescope, the 1-mile telescope, the low-frequency synthesis telescope at 151 MHz and the long-baseline interferometer system at 81·5 MHz. Research on image analysis has continued and some fundamental limitations of the CLEAN algorithm have been exposed.

Technical activities have formed an abnormally large part of our programme. Work on cooled receivers for the 5-km telescope has continued and major construction for increasing the bandwidth to 350 MHz on 28 baselines has commenced. Excellent progress has been made in the conversion of the low-frequency synthesis telescope to 38 MHz in order to exploit the imminent period of sunspot minimum and observations will begin in 1986.

Undoubtedly the greatest technical effort has been directed towards the James Clerk Maxwell Telescope during the final construction phase on Mauna Kea. Contracts for the control and data-handling systems have been successfully completed and the 220–280 GHz receiver for commissioning has been built and is about to be shipped.

Good progress has been made in establishing the feasibility of aperture synthesis at optical wavelengths. This work is being carried out in collaboration with IOA. The use of closure phase has been successfully demonstrated and diffraction-limited images with a resolution of 0·08 arcsec have been obtained.

## 2 SOLAR SYSTEM

*Interplanetary transients.* A full analysis has been completed of all significant transients that were detected during the sky survey made with the 3·6 hectare array over the period August 1978–September 1979. A total of 96 disturbances has been analysed and in all cases back-projection to the sun's surface indicated coronal holes as the sources (Hewish & Bravo–Nunez, in press). This work is of fundamental importance to solar-terrestrial physics where the consensus view is that energetic disturbances are generated by solar flares and erupting prominences. Presentation of these observations at the *XIX*th General Assembly of the I.A.U. aroused a lively discussion (Hewish, in press).

The unique capability of scintillation to determine the location of transients

in the heliosphere, when combined with *in-situ* measurements of shock-accelerated particles obtained by spacecraft, can provide valuable information on shock acceleration mechanisms. A preliminary analysis of 45 interplanetary shocks has shown a very strong dependence of the energetic particle flux upon the direction of travel of the disturbance-centre relative to the sun–earth line. This observation can be understood in terms of the direction of the shock-normal relative to the prevailing interplanetary magnetic field, and confirms one theory of particle acceleration by shocks.

Direct comparison of scintillation and spacecraft density measurements has shown that scintillation provides a reliable estimate of mean plasma density along the line of sight under both quiescent and disturbed conditions. No evidence was obtained for enhanced density fluctuations in post-shock flows (Tappin 1986).

## 3 GALACTIC

3·1 *Supernova remnants.* Tan & Gull (1985) have made detailed studies of the expansion of Tycho's supernova remnant from pairs of observations made at intervals of 3 and 15 years at 1·4 and 2·7 GHz with the OMT and 5-km telescopes respectively. Using a new algorithm for comparing the maps they deduce an expansion of the form $R \propto t^{0\cdot462\pm0\cdot024}$ – marginally faster than expected for Sedov expansion. Different types of behaviour are detected at different position angles, indicating the scale of inhomogeneity of the surrounding medium.

Green & Gull have made high-resolution observations of compact Galactic plane sources in a search for young but distant SNRs. One such source G227·1 + 1·0, previously believed to be a young SNR, has been shown by HI absorption observations to be an extragalactic source akin to 3C310 (Green & Gull 1986). Green (1985) presents the results for the other 42 sources in the search that are thought not to be SNRs because of their structure or spectra. However, some of the flat-spectrum objects could be 'filled-centre' remnants rather than HII regions. Indeed, other workers have made further observations that reveal one new 'filled-centre' remnant among these sources. They also suggest that G70·68 + 1·20, a small shell source, is in fact a *very* young shell remnant rather than a thermal source as proposed by Green (1985), because of its apparently nonthermal spectrum. The nature of G70·68 + 1·20 has been discussed further by Green (1986a) who presents new 5-GHz observations, and reviews other available data.

New radio observations of 3C58 (the 'filled-centre' remnant of the SN of AD1181) at 151 and 2695 MHz are presented by Green (1986b), together with studies of its X-ray emission from data obtained from the EINSTEIN data bank. These provide a low upper-limit on the luminosity of any shell around 3C58 and suggest that SN1181 did not produce the fast shell of ejecta that is predicted by some current theories of 'type II' SN.

A detailed comparison of maps of Cassiopeia A at 5 GHz made in 1974 and 1978 with a resolution of $\simeq$ 2 arcsec has been made by Tuffs (1986). These show a clear expansion (both for compact and broad-scale features) on a timescale about three times that of the fast optical filaments. Several intense compact radio peaks situated near the periphery of the radio plateau have

individual outwards motions significantly slower than is predicted for swept-up matter downstream of a blast-wave propagating in a uniform external medium. Proper motions are independent of the sign of brightness changes, and unlike the fast optical filaments the radio peaks have non-systematic components of motion.

Downes, Pauls & Salter (1986a) present 5-GHz observations of the supernova remnant W50, which contains SS433. The spectrum of W50 is typical of that of old shell SNRs, and shows no evidence for the injection of flat-spectrum particles from SS433. The northern boundary of that remnant is bright, strongly polarized, and has a slightly flatter spectrum than the rest of the object; the magnetic field direction, where it can be detected, is tangential to the shell. The bright northern edge appears to be a typical example of compression of a large-scale interstellar magnetic field. The shell of W50 has bright regions which coincide with the position angles of the precession cone of the jets from SS433.

Albinson *et al.* (1986) present maps of the HI in the direction of 3C10, Tycho's SNR, which indicate a distance of 1·7–3·7 kpc for the remnant. The structure of the HI in this direction is complicated, with numerous arcs and filaments, some of which appear to be expanding shells. These shells have HI kinetic energies of up to $10^{43}$ J, and it is proposed that stellar winds are responsible for two of the features. Various objects – an open cluster, individual stars and two CO clouds – are associated with minima in HI emission, although other CO clouds, and an HII region coincide with HI emission features.

Observations of IC443 at 151 and 1419 MHz are presented by Green (in press). These detect non-thermal emission from the region of faint optical filaments to the northeast of IC443. Comparison of the 151- and 1419-MHz maps reveals a region of flatter than average spectrum in the southeast, contrary to other recent spectral index maps of the object. This comparison also suggests that the brighter northeast of IC443 has a flatter spectrum than the faint southwest, and it may have a spectral break – these differences are presumably due to differing emission mechanisms or conditions in these regions.

3·2 *Molecular line observations.* While much of the millimetre group's energy has been absorbed by the work on the JCMT, several observing programmes have continued at UKIRT and at other telescopes. We have now installed a proper spectral-line reduction package at UKIRT, so that the preliminary stages of data reduction can be done there, and reduced spectra transferred over the network for evaluation at MRAO. As a result of both the improved observing efficiency and the much improved receiver we are at last able to obtain data of the quality required to keep up in this intensely competitive field.

Cox and Scott have continued their search for new star-forming regions using UKIRT and the Onsala 20-m telescope. Two previously unknown sources were found, one of which, in the Cygnus region, probably lies at a distance of about 500 pc and has a kinetic temperature of around 50 K. $HCO^+$ $J = 1 \rightarrow 0$ emission from the other source is extended over several arcminutes.

Cox, Scott and Russell have made $HCO^+$ maps of W51, with the Onsala telescope in the $1 \rightarrow 0$ transitions of both the main line and that of the less-abundant species $H^{13}CO^+$, and in the $3 \rightarrow 2$ main line with UKIRT, using the new MRAO dual-polarization receiver. The Onsala observations show a strong extended continuum source, with a brightness temperature of 0·8 K. The flux is consistent with an optically-thin thermal spectrum extrapolated from lower frequencies – there is no evidence for the enhancement by a factor of three claimed by the Helsinki group. Extensive self-absorption is seen in the $J = 1 \rightarrow 0$ line; absorption is also seen against the continuum in the lower frequency observations. Detailed analysis suggests that the excitation temperature of the absorbing gas is less than 3·5 K, and that it is probably associated with the high velocity $H^0$ stream overlying the source, not with low density envelope material.

Russell has mapped the $HCO^+$ $3 \rightarrow 2$ main line in DR21 and Orion B (NGC 2024) with the MRAO receiver on UKIRT. In DR21 the general morphology agrees well with that shown in published $H_2$ and CO data. In Orion B he sees red and blue shifted high-velocity emission in a bipolar distribution similar to that of the CO but of reduced angular extent. This may be evidence for an overall density gradient in the flow (in contrast to the clumpy models propounded elsewhere).

In collaboration with Bally, Russell has observed $H^0$ in DR21 and Cep A with the VLA in D-array. He finds a general anti-correlation of $H^0$ with $H_2$, and additionally, in DR21, he sees a strong jet-like structure in P.A. 90°.

Lewtas has observed Sgr B2 in several emission lines of $SO_2$. The lines near 3-mm were observed with the FCRAO 14-m antenna and those near 1-mm with the NRAO 12-m antenna on Kitt Peak. $SO_2$ has a highly complex spectrum, since it is an asymmetric rotor, and conventional numerical modelling of the radiative transfer and excitation is therefore quite difficult. Lewtas has succeeded in modelling the excitation structure and, using her model, has identified several hot, dense clumps within the extended Sgr B2 molecular cloud. She has also observed a number of rotational transitions of the symmetric-top molecule $CH_3CN$ – analysis of the relative strengths of the lines in separate K-ladders gives a good estimate of the kinetic temperature in the source independent of density.

Parker has re-measured the positions and sizes of the class VI dark clouds from the Lynds survey. He finds significant errors in the published catalogue, and is preparing to publish a revised version, which will also be available on the Starlink system.

A library of molecular line modelling programs has been collected on the group's MicroVax II computer. This includes versions of most well known codes, as well as a number devised at MRAO, in particular by Padman (for a microturbulent cloud) and Martin (for a clumpy macroturbulent cloud). Parker has written a set of programs to do chi-squared fitting of molecular line data to model predictions.

3·3 *Galactic centre.* Lasenby has collaborated in measurements with the Bonn 100-m telescope at 10·7 GHz which reveal a new symmetrical polarization structure near the Galactic Centre (Seiradakis *et al.* 1985). This has a 'core/lobe' morphology with major axis aligned along the filaments of the

radio Continuum Arc, and with an appearance reminiscent of a classical double radio source.

Lasenby, Lewtas and Yusef-Zadeh, using the VLA in C/D configuration, have made HI absorption maps covering a large region near the Galactic Centre, in an effort to shed light on the positional and dynamical relationships between the continuum sources and the distribution of molecular material, about which there has been much controversy. Preliminary analysis has revealed an unexpected deficit of gas at 50 km $s^{-1}$ in front of the Continuum Arc, thus making difficult the unambiguous placing of the Arc at the Galactic Centre.

3·4 *Pulsars.* Collaborative work with teams from Groningen and Arecibo has been carried out to investigate rapid-pulsar candidates drawn from the second IPS survey (Stevens *et al.* 1984). Some aspects of the history of neutron stars, their discovery, and the consequent impact on astrophysics have been discussed by Hewish (1986).

## 4 EXTRAGALACTIC

4·1 *Star formation.* Cox and Eales have constructed flux-limited samples of the 6C (151 MHz) radio survey and the IRAS survey, in a region covered by the CFA optical redshift survey. There is a strong correlation between infrared and radio fluxes. Essentially all the objects in the sample are associated with late-type (spiral, peculiar and irregular) galaxies. As the 151 MHz fluxes are necessarily non-thermal, this implies that the non-thermal radio flux from these galaxies is associated with young stars. From modelling work they have shown that less than 10 per cent of the radio flux is from supernova remnants, so the bulk must come from cosmic-rays generated in SNR but radiating elsewhere in the galactic magnetic field. A consequence of this is that SN rates have been overestimated in the past by an order of magnitude.

Markarian 231, a type I Seyfert of $10^{12}$ solar luminosities and the most luminous object in the sample, lies right on the regression line. This confirms that the luminosity is due to a starburst. One or two other very luminous sources can be similarly interpreted.

The dust temperature can be derived from the IRAS 60 $\mu$m and 100 $\mu$m fluxes. There is a close correlation of $T_d$ with total luminosity. More particularly, $T_d$ is also correlated with the ratio $L_{\rm ir}/L_{\rm bol}$, so that it is clear that the dust temperature is due to star formation. The sample is divided into two easily distinguished classes. For values of $L_{\rm ir}/L_{\rm bol}$ less than $\simeq 3$ virtually all sources are normal spirals, while for higher luminosity ratios more than 50 per cent of the sources are peculiar or interacting galaxies, and the correlation is much weaker. They conclude therefore that in general interaction of two galaxies may trigger intense bursts of star formation.

4·2 *Source surveys and observational cosmology.* This year saw the publication (after a long gestation period) of the first part of the 6C Survey (Baldwin *et al.* 1985). The survey covers most of the sky north of declination 30° with an angular resolution of $4{\cdot}2 \times 4{\cdot}2$ cosec $\delta$ arcmin$^2$ and a limiting flux density

of 120 mJy at 151 MHz. This first paper describes the telescope and the methods of observation, calibration and data analysis. Maps of a circular area of radius 10° centred on the the North Celestial Pole are presented and 1761 sources north of declination 80° are listed. Several papers have already been published which make extensive use of these North Pole data and the data from other zones of the survey. Since one of the most important aspects of the 6C survey is its completeness for low surface-brightness sources of large angular size, these papers have concentrated on studies of individual large sources or on statistically complete samples free from the angular size selection effects.

The 6C telescope was used in a slightly different manner to search for primordial pancakes; these collapsing protoclusters at redshifts in the range 3–20 should be detectable through their 21-cm neutral hydrogen emission. Bebbington (1986) made a search for the redshifted 21-cm line emission from such objects in the region of sky around the North Celestial Pole. No sources were found in a one per cent redshift range around $z = 8{\cdot}4$, the nominal survey redshift. Baldwin (in press, a), in a paper presented at the IAU in Delhi, reviews the current situation with regard to the search for primordial pancakes and derives typical physical parameters for them. The observations of Bebbington and others have all resulted in upper limits on the 21-cm line emission from these objects at various redshifts. These data place strong constraints on the largest mass scales involved, though their interpretation is not unique and depends on the assumed value of $\Omega_0$.

As well as detailed studies of the cosmological evolution of sources selected at low frequencies (Eales 1985a, b, c), much work has been done in a similar study at high frequencies. A high frequency sample allows constraints to be put on the population of compact flat-spectrum objects, which appear at these frequencies in addition to the extended sources familiar from low frequency surveys. Downes *et al.* (1986b) have constructed a complete sample of extragalactic sources with flux densities $\geqslant 0{\cdot}1$ Jy at 2·7 GHz from the Parkes selected regions, their aim being to examine the evolution of the radio luminosity function at high luminosities. By comparing the observed magnitude distributions with the predictions from samples at high flux densities, Downes *et al.* conclude that the co-moving density of powerful radio sources starts to drop at redshifts $\simeq 2{\cdot}5$. Further confirmation of this drop has come from deep identification work and spectroscopic observations of some of the objects. Most notable amongst these is the compact flat-spectrum object 1351–018, which is found to have a redshift of 3·71 (Dunlop *et al.* 1986), making it the second most distant quasar known. It is of additional interest in that it is optically very faint, and in common with other high-redshift radio-loud quasars has relatively weak emission lines. It is likely that similar objects will have been missed by optical searches for high redshift quasars.

Birkinshaw (1986) has used the 1-mile telescope to make a deep survey (5C20) of the region centred on Abell cluster A2218. Several of the sources found are identified with galaxies in Abell clusters in the field; he also detects a faint radio halo in A2218. The source counts, spectral index distributions and identification statistics are similar to those found in earlier surveys.

The IPS survey at 81·5 MHz has now been fully reduced and a catalogue of some 1800 sources has been prepared (Purvis *et al.* 1985). For each source

the scintillation versus solar elongation curve is given together with the derived angular size (predominantly in the range 0·1–1·0 arcsec) and the flux density contained within the compact component(s). Also presented are the averaged scintillometer records so that further data may be extracted if required. For example, it might be useful to obtain an upper limit to the flux density of any compact feature within a particular source not listed in the catalogue. This value could be derived from the scintillometer record.

4·3 *Radio sources and their physical environments.* Spinks, Rees & Duffett-Smith (1986) have mapped the double radio source Cygnus A at 81·5 MHz using a two-element interferometer with variable orientation and spacing (maximum 45 km). This is the lowest frequency at which the radio source has been mapped with sufficient resolution (16 arcsec) to resolve the bridge of emission joining the two outer lobes. By comparing the low-frequency map with one made at 2·7 GHz by Alexander, they obtain the variation of spectrum along the bridge and an estimate of about $3 \times 10^6$ yr for the age of Cygnus A.

Miller has followed up his investigation of the dynamics of some 3CR double radio sources (Miller 1985), with an analysis of the gaseous environments of five of these objects (Miller *et al.* 1985). X-ray maps of the regions around these sources were obtained using the Image Proportional Counter of the Einstein Observatory. The X-ray sources were unresolved and are likely to be associated with the nuclei of the radio galaxies. However, the data provide good upper limits on the X-ray emissivity of the regions around the radio lobes, and, when combined with the expected behaviour of hot gas in and around the lobes, show that most of the radio-emitting plasma is unlikely to be maintained in static pressure-balance with an external medium. A simple model consistent with the observations is one in which the radio lobes continuously expand into the external medium, with a consequent decrease in radio luminosity with time. From the X-ray observations it is also possible to place a lower limit of about one-tenth of the equipartition values on the magnetic fields in the lobes.

Leahy, Pooley & Riley have made multifrequency polarization observations of two samples of bright extragalactic radio sources using the 5-km telescope at 6 and 11 cm and the VLA at 18 and 21 cm with resolutions $\simeq 5$ arcsec. The samples, at low and high galactic latitudes respectively, were selected to give insight into the magnetic field and rotation measure (RM) structures of typical sources, and to allow the separation of galactic foreground effects from those local to the source. In the first of several papers discussing these observations, Leahy *et al.* (submitted) give maps for 31 classical double sources and present some preliminary conclusions. Galactic foreground effects clearly dominate the RM distributions at low galactic latitudes, but the RM variations at high latitude are mainly intrinsic to a source and occur on scale sizes typically one-tenth of its overall size.

To investigate the pattern of radio activity in giant E and So galaxies, Cordey (1986) has selected a sample of 67 such galaxies from the Harvard CFA Redshift Survey. Using new and existing observations, all with high sensitivity to low surface brightness emission, Cordey confirmed the preference of radio sources to be associated with E rather than So galaxies. Using

arguments based on the evidence for continuing nuclear activity in the sources in his sample with $P_{2380} > 10^{23}$ W Hz$^{-1}$, and on typical radiative lifetimes at 151 MHz, Cordey concludes that the time-scale over which typical radio galaxies remain active is greater than $3–4 \times 10^9$ years.

4·4 *Theoretical studies of radio source physics.* The study of computational fluid dynamics complements three major areas of observational interest within the group: extragalactic radio sources, jets from young stars, and studies of anisotropies in the microwave background radiation. Despite comparatively meagre computing resources, MRAO currently enjoys the world lead in simulations of extragalactic radio sources. A significant advance in our understanding has been the discovery that the principal observational classification by Fanaroff and Riley can be reproduced by axisymmetric simulations of light trans-sonic jets. Preliminary low-resolution non-axisymmetric (i.e. three-dimensional) simulations have reproduced many of the detailed features of radio sources, such as the asymmetric internal double structure of hotspots, in terms of a model involving small changes in the direction of the jet.

Current work has concentrated on the specifically fluid-dynamical properties of extragalactic sources, such as the shock structure of knots and hotspots (Williams, in press), and the effect on source morphology of a galactic atmosphere and motion through the intra-cluster medium. Our understanding has now reached the stage at which to start high-resolution three-dimensional calculations to incorporate more sophisticated modelling of the radio emission.

Cawthorne has studied the problem of the flux variations of extragalactic sources at low radio frequency (< 1 GHz). In one paper (Cawthorne & Rickett 1985), he investigates the suggestion that the variability is the consequence of refractive (rather than diffractive) focussing by the interstellar medium. He shows the expected correlation of variability with galactic latitude to be undoubtedly present, although the mechanism is unlikely to explain the variability in all cases. In a second paper (Cawthorne 1985), he explores the possibility that the variation might be intrinsic, as a result of the presence of thermal plasma in the synchrotron source. He concludes that the simplest models of the synchrotron masers that can then occur still cannot account for brightness temperatures as high as $10^{14}$ K at 400 MHz because of Compton scattering restraints, though these may be alleviated by geometrical and kinematic factors.

Cawthorne & Scheuer have considered the problem of sources with apparent superluminal motions and the difficulties of using source statistics for setting constraints to theoretical models of the behaviour; a valid sample for such work needs to be one selected without regard to the flux from the central component in which the motions are observed. Cawthorne *et al.* 1986 assemble such a sample, using existing maps where appropriate and otherwise making new observations with the VLA and with MERLIN, to ensure the selection criteria are applied to the extended structure alone. They describe the sample and the new observations and discuss the constraints to models that can be applied by using it.

4·5 *Microwave background.* At the ESO-IRAM-Onsala conference on (sub)-millimetre astronomy, Lasenby & Gull (1985) gave a review of the exciting prospects for millimetre wavelength investigation of cosmic microwave background anisotropies and of the Sunyaev–Zel'dovich effect in emission, once the new generation of dishes and receivers have been completed. The review pointed out that problems encountered in centimetre wavelength measurements of this kind would still be present at millimetre wavelength, and would need careful experimental design in order to overcome them.

Saunders (in press) has explored in detail the merits of interferometers for sensitive microwave background observations and identifies the advantages over single dish measurements in the areas of spillover, tropospheric emission, sensitivity and the interpretation of the observations. He also considers the question, important at least at present in microwave background astronomy, of ascribing an upper limit to a quantity given its non-detection in an experiment; this is proving a fertile area for exposing the problems of the different approaches (Bayesian, frequentist and fiducial) to statistics.

## 5 TECHNIQUES

5·1 *Astrometry.* Andrei is concerned with updating and improving reduction procedures used for astrometry with the 5-km telescope and is pursuing the measurement and correction of atmospheric effects.

5·2 *Methods of data reduction: maximum entropy.* The popular CLEAN algorithm has been thoroughly analysed by Tan (1986). The eigenvalues of the (Toeplitz) dirty-beam matrix are crucial to the understanding of the performance of the algorithm. With perfect arithmetic, and using the (slow) discrete Fourier transform to make the dirty map, the algorithm must converge, but the solution to which it converges is a chaotic function of both the loop-gain and of the starting image. If imperfect arithmetic and/or non-optimal gridding produce stray negative eigenvalues, then the algorithm must ultimately diverge. The 'corrugation effect' is a transient phenomenon that places flux into unmeasured eigenvectors but does not, as probably believed, depend on the existence of negative sidelobes in the beam. Smoothness stablised CLEAN, on the other hand, must ultimately converge and all transients effects disappear, because the 'Prussian hat' beam is positive definite. Unfortunately, the solution to which it converges (in the absence of windowing) is the principal solution, which does not have desirable properties of smoothness and sidelobe suppression. The fact has so far escaped attention because the CLEAN algorithm is not in fact capable of convergence in reasonable computing time. Modern preconditioned conjugate–gradient algorithms for the solution of matrix equations, however, clearly demonstrate this behaviour, but at the same time offer the prospect of great savings of computer time.

None of these drawbacks apply to the maximum entropy method (MAXENT) which continues to be the subject of an active research group throughout the University. Reviews of the work of this group have been published this year by Skilling & Gull (1985), by Gull & Skilling (1985) and by Gull & Newton (in the press).

Gull & Newton (1986) discuss MAXENT as a technique for tomographic reconstruction. A traditional justification of the method (based on observation of the behaviour of kangaroos) is supplemented by state-of-the-art tomographic images of nuclear fuel bundles. These pictures illustrate the additional power of prior information when faced with limited angle coverage.

Gull & Fielden (in press) begin to apply Bayesian methods to that branch of statistics usually called 'non-parametric'. This field is particularly important in observational sciences. They show how to estimate the median and other quantiles of a probability distribution from a sample, making only minimal assumptions about its form. The results are novel and provide a first example of a class of statistical problems that require the use of both MAXENT and Bayes' Theorem. Gull (in press, a and b) extends this class to cover the estimation of spectra of time-series and to the properties of traffic-jams.

Garrett (in press) has suggested that the uncertainty principle of quantum mechanics is best viewed in an information-theoretic form, rather than as an inequality connecting variances of conjugate variables. It is certainly true that the entropic version of the theorem implies the more traditional one, but not vice-versa, but it is not yet clear whether this extra power gives any real advantage.

5·3 *High resolution optical imaging*. An important new extension of radio astronomy techniques has been the application, in a collaborative programme between MRAO and the Institute of Astronomy, of aperture synthesis and closure phase measurement to high resolution imaging with large optical telescopes.

Warner (1984) has emphasized the over-riding importance of phase measurement in radio astronomical imaging. Examples from the early history of the subject illustrate the errors of physical interpretation of the images that were made when phase information was lacking or when false assumptions about its behaviour were made. Recent work has shown that correct reconstructions of images can be made without phase information in special cases but that, in general, phase measurements are essential. This result is expected to be equally important in optical imaging. A programme to establish methods of obtaining such phase information for optical imaging has been in progress here over the last year.

The observations with the University of Hawaii 88-inch telescope using short exposure CCD images taken through non-redundant aperture masks, which have now been fully analysed (Baldwin *et al.* 1986), give several results which are very important for future high resolution imaging with large telescopes.

Firstly, interference patterns are readily detectable using non-redundant arrays of small apertures in the pupil plane. Trials using a variety of numbers, layout patterns and sizes of holes all showed the diffraction Airy disk for a single aperture crossed by fringes corresponding to baselines between every pair of apertures. The fringe visibilities were high for exposure times less than $\simeq$ 50 ms. Secondly, the phases of the fringes, when added round triangles of baselines, give closure phases exactly equivalent to those used in VLBI in

radioastronomy. Tests on an (unresolved) star gave closure phases with a small scatter about the expected value of zero for exposure times $\leqslant 100$ ms. Averaging of many exposures should give accuracies of better than 1° which, from experience in radioastronomy, will give diffraction limited images with high dynamic ranges. Thirdly, a small number of exposures taken with 45 cm diameter apertures showed images of each aperture which were virtually diffraction limited (0·3 arcsec) but moving relative to one another by $\simeq 0{\cdot}2$ arcsec. If such images could be superposed accurately by autoguiding, then the sensitivity of the interferometric techniques should be greatly improved and high resolution imaging might be achieved for objects as faint as +13 mag.

The first diffraction limited image of a star using aperture synthesis has just been obtained by us from recent observations (November 1985) on the Isaac Newton Telescope using aperture masks with the IPCS as detector. A mask composed of a linear array of four 5-cm apertures giving 6 baselines up to a maximum separation of 1 m was used in 9 position angles relative to the star $\lambda$ Peg (+4 mag). Closure phases accurate to better than 5° were obtained for all baselines by averaging many exposures. Some fall-off in fringe visibility with baseline is seen which is thought to be atmospheric in origin. The resolution achieved is 0·08 arcsec and the dynamic-range in the image is $> 50{:}1$. The result is not astronomically interesting, since the star is expected to be unresolved, but it demonstrates that the method is both practical and powerful. Analysis of data on a double and a triple star is in progress.

Further observations aimed at exploring the full resolution of the INT (0·03 arcsec) and improving the sensitivity of the method are planned for the immediate future.

## 6 INSTRUMENTAL

6·1 *5-km telescope*. The sensitivity of the 5-km is being increased by a factor of 20 by two major programmes of upgrading, the fitting of cooled FET receivers and the broadening of observing bandwidth. The main scientific aims of the upgraded telescope are (a) to map the Sunyaev–Zel'dovich decrement in cluster gas over wide ranges of cluster type and redshift; (b) to search for primordial anisotropies in the microwave background radiation on arcmin scales at levels $\Delta T$ an order of magnitude better than those attainable with any other instrument; (c) to investigate the physical causes of the cosmic evolution of radiosources.

### (*a*) *Cooled receivers*

Work is continuing on the design, construction and testing of cooled FET receiver systems at 5, 15 and 2·7 GHz. These replace the existing (uncooled) parametric amplifier front ends in order to reduce the system noise temperature by a factor of three in all three bands.

The prototype cryostat containing two 5-GHz FET amplifiers has been installed on one aerial of the telescope and operating satisfactorily for several months. The system performs well and provides an overall system temperature of 60 K, representing an improvement of more than a factor of

three. As had been anticipated, the performance of the rotating joint (used in measurement of polarization) was less than ideal and as a temporary measure the joint has been removed while further investigation of the possible replacements proceeds.

In order to install the cryostat, a new cable-wrap system (which should also be more reliable and easier to maintain) has been installed, including provision for the helium lines to the cooling head. These mechanical modifications are now being carried out on the remaining seven aerials, while the production versions of all eight cryostats are being assembled.

At 15 GHz, a prototype amplifier has been constructed, based on a design supplied by the National Radio Astronomy Observatory. It can be mounted within the same cryostat as the 5 GHz amplifier. Copper coated plastic waveguide is planned for the input line to the 15 GHz amplifiers; it has the necessary thermal insulation, and identical electrical properties to conventional copper waveguide. These waveguides are currently under test for their physical and electrical immunity to thermal cycling.

At 2·7 GHz, the larger physical size of the amplifiers necessitates a separate cryostat. Both amplifier and cryostat designs are at a very early stage.

At all frequencies, amplifier testing is to be facilitated by the construction of an automated noise figure measurement system. Based around a BBC micro, it is capable of setting and monitoring the bias conditions of up to three FETs simultaneously, while sweeping frequency, controlling a noise source and measuring the output noise power. As well as speeding the testing of single stage amplifiers, it should allow the optimization of bias currents and voltages to individual transistors in a multi-stage design for best noise figure, a process that would be extremely tedious manually.

### (*b*) *Broad-banding*

This has been the first year of major construction in the programme to increase the 5 km bandwidth from 10 to 350 MHz, and to include simultaneous correlation on all 28 possible baselines.

The block design of the broad-band system was formulated during 1984 and is as follows. For the standard observing frequencies of 2·7, 5·0 and 15·4 GHz, a new phase-switched filter-mixer system produces a 350 MHz single-sideband IF. Equalizer-amplifiers in the underground cables compensate for differential attenuation across the IF band. In the control room new filter-mixers split the IF from each aerial into $5 \times \pm 35$ MHz double-sideband signals, fringe demodulation being provided by rotating the phases of the tuneable local oscillators. The signals then undergo 2-bit A-to-D conversion at 70 MHz, serial to parallel ($4 \times 17{\cdot}5$ MHz) conversion, and path compensation in ECL digital delay; coherent signals at 17·5 MHz clock rate are then available for correlation. The correlation is done by CMOS semi-custom ICs, which multiply each pulse derived from a particular $\pm 35$ MHz channel by the 7 to 0 previous and 8 subsequent pulses from the same channel from each of the other 7 aerials. These cross-products are then FF transformed and sub-channels 15 MHz wide are synthesized. Maps can then be made from these sub-channels, enabling channels with interference to be rejected and chromatic aberration to be avoided.

In the major task of implementing the above system, the main technical developments during the year have been in the areas of the local oscillator and IF splitter system, with the problems of equalization across the 100–450 MHz band and stringent isolation between different channels, the 70 MHz A-to-D converter, and the correlator, where work on the semi-custom IC chips is nearing completion.

6·2 *Millimetre-wave telescope.* The James Clerk Maxwell Telescope (JCMT) is now essentially complete on Mauna Kea, and commissioning tests are underway. The first astronomical observations are expected to take place in mid-July 1986. Progress has been reported at Aspenas by Hills (1985) and at a number of other meetings.

(*a*) *Control system*

The team led by Scott has been entirely responsible for the control and data-handling system. This work has gone exceedingly well – the VAX 11/730 computer, telescope and carousel engineering consoles and all microprocessor systems have now been delivered to Hawaii, and a first version of the control software has been used for drive tests.

(*b*) *Data handling*

Fairclough and Padman have devised a 'General Single Dish Data' (GSDD) format, after consultations with representatives of NRAO and IRAM. This VAX-specific format is efficient with respect to disc and tape space required, and can be easily extended to deal with new types of observation in a completely general way. Padman has detailed the calibration facilities required, in a general form which takes account of the fact that the telescope will have both heterodyne (single-mode) and bolometric (multi-mode) detectors. She has shown that the practice of sky-dipping can be avoided if facility is made for the receiver to see the sky without looking through the Cassegrain optics of the telescope.

(*c*) *Other*

The telescope requires two tertiary mirrors – one 45 ° rotating plane mirror to feed the four receivers at the folded Cassegrain foci, and a second convex mirror to produce an f/35 beam at the Nasmyth focus on the elevation axis. This second focus is particularly important since it is compatible with the f/35 UKIRT Cassegrain focus, and therefore facilitates interchange of instruments between the two telescopes. These mirrors have now been manufactured in the University of Cambridge Department of Engineering, to specifications provided by Hills.

At the ESO-IRAM-Onsala conference on (sub)millimetre astronomy, a comparison of holographic and mechanical methods of measurement of the surface profiles of large reflector antennas was given by Lasenby (1985), with particular reference to the NRAO 12-m antenna, including the results achieved to date.

## 6·3 *Millimetre-wave receivers*

### (*a*) *UKIRT MkII* (*Dual-polarization*) *receiver*

Initial problems with the dual-beam system have now been overcome, and the instrument has been used on a number of occasions for observations during 'morning twilight'. With a number of minor improvements to the system the noise temperatures in the two channels are now roughly 800 K and 1000 K DSB. Murphy has continued to work on the 345 GHz indium antimonide 'imaging' system. Details of both the imaging system and the dual polarization system were presented at the Cannes meeting of the SPIE in 1985 by Barker *et al.* (in press).

### (*b*) *JCMT 230-GHz commissioning receiver*

The contract for this receiver was placed with MRAO in April 1985, and the design finalized in May 1985. The receiver has now been completed by a team led by Padman for delivery to Hawaii by the end of April 1986. While in many ways a logical continuation of the 270 GHz UKIRT MkII receiver, it incorporates a novel design of dual polarizing Michelson interferometer, which gives identical paths for the two polarizations in a physically compact form. This is the first millimetre-wave receiver built at MRAO to use closed-cycle refrigeration, and we have benefited from the experience with the 5-km cryogenic system.

As a result of the design study for the mixer feed-horns, major advances were made in our understanding of the beam propagation and coupling in such quasi-optical systems. Padman, Murphy & Hills (submitted) have shown that the highest aperture efficiency for a Cassegrain antenna is obtained when the antenna aperture is imaged onto the feed-horn aperture in a frequency-independent way, which will normally involve the use of some tertiary optics. The tertiary focus thus formed is an ideal position at which to place beam shaping systems to improve the aperture illumination still further. Some of these ideas have been incorporated in the new receiver.

The mixer elements are Shottky diode fixed-backshort mixers built at the Rutherford Appleton Laboratory. In this receiver they give noise temperatures of 710 and 820 K SSB, which implies that the RF losses in the front end and IF amplifier noise temperatures must both be exceptionally low. A key component in any mixer system is the first IF amplifier – we have used 4 GHz cooled FET amplifiers built at MRAO by Bly. These are similar to those built for the UKIRT MkII receiver which have since been described in the literature (Withington 1984).

### (*c*) *SIS*

Most SIS junctions used in astronomical receivers at present use lead-alloy junctions, which are relatively fragile, and usually fail after a small number of thermal cycles. The Cambridge University Department of Engineering is now making robust all-niobium SIS junctions on quartz, to specifications provided by Withington. As part of the development work, Withington

(submitted) has described a novel mm-wave tunable backshort structure, which uses a flexible bellows as a length of corrugated waveguide.

6·4 *The Low Frequency Synthesis Telescope.* The telescope has been in continuous operation throughout the year at 151 MHz, without significant changes in its performance. Earlier work leading to publications is discussed under the relevant headings elsewhere in this report. The main observing programmes with the telescopes during the last year have been of deep samples of sources over wide areas of sky and regular monitoring (at three epochs so far) of flux densities as part of a survey to establish the properties of Low Frequency Variables. In addition a shallow survey is being made to cover the region $15° < \delta < 55°$ with a resolution of $71'' \times 71''$ cosec $\delta$ and an rms noise of $\simeq 20$ mJy at 151 MHz; the survey will contain 180 fields and will provide the most comprehensive coverage yet available at this range of declinations.

An important improvement in the methods of analysis of the LFST data has been the development of programmes for fitting source positions and flux densities which take full account of the aberrations of the telescope and allow automatic reduction with positional accuracies of 1–2 arcsec even at distances as large as 2° from the beam centre.

A description of the LFST and its performance has been given by Baldwin (in press, b); its relationship to the complete range of synthesis telescopes has also been summarised (Baldwin 1985).

Preparation for conversion of the LFST to operation at 38 MHz has made substantial progress during the year. 60 lamp-standard poles have been erected to support the ten-element Yagis in groups sited along the 5 km baseline of the telescope. Trial observations have been made on 16 baselines enabling tests of the local oscillator system, correlator and software to be made. Full operations to give mapping with 4 arcmin resolution over a large part of the northern sky will start during the early summer and are expected to last for about one year.

6·5 *Long-baseline interferometry at 81·5 MHz.* Our programme of long-baseline interferometry at 81·5 MHz has continued with the mapping of Cygnus A using the two-element version of the portable interferometer (see elsewhere in report). A third recording terminal has now been completed and installed in its motorcaravan, and will be used initially in conjunction with the Mark III dish at Jodrell Bank.

6·6 *Additional computing facilities.* A MicroVAX II was installed towards the end of 1985 for (a) continuing the work on numerical simulations of radio sources, and (b) further development work on JCMT software; with extra memory (7 Mbyte total) and when running CPU-intensive programs, it approaches the speed of a VAX 11/780. The connection of the computer to the PSS network has proved invaluable for keeping in touch with the work (including software development) in Hawaii. The radio source simulations can be run, as batch jobs, with insignificant degradation in interactive performance, and obtaining 23 h, or more, of CPU time per day. It is hoped to enhance the system by the addition of a larger (and faster) disk during 1987.

## 7 MISCELLANEOUS

Duffett–Smith (1985) has published a new book entitled '*Astronomy with your personal computer*', complete with the software made available on floppy disc for a number of commonly-used machines.

## 8 GENERAL

Lectures were given by members of the observatory at the following conferences:

IAU General Assembly XIX, Delhi, India
IAU Symposium No. 119, 'Quasars', Bangalore, India
Symposium on Cosmology, Vatican Observatory
Workshop, 'Energetic particles and their effects in supernova remnants, galaxies and jets', Schloss Ringberg, W. Germany
Workshop on Extragalactic Jets, Munich
ESO-IRAM-Onsala Workshop, '(Sub)Millimetre Astronomy', Aspenas, Sweden
SPIE Conference on Instrumentation for Submillimetre Astronomy
5th Workshop, 'Maximum entropy in spectral estimation and other problems'
IEE Colloquium, 'Inverse Methods in Image Processing'

Hewish has continued to chair the National Committee of Astronomy and to serve on the SERC-ZWO Joint Steering Committee and on the James Clerk Maxwell Telescope Management Committee.

Baldwin is President of Commission 40 (Radio Astronomy) of the IAU and a member of the Australia Telescope Advisory Committee and has been a member of PATT.

Scheuer has continued to serve on the ASR Theory Panel and the MERLIN Programme Committee and has joined the EVN Programme Committee.

Hills continues to act as Project Scientist and Padman as his deputy on the various committees concerned with the James Clerk Maxwell Telescope.

Duffett–Smith has served as a member of the Astronomy I Committee of the ASR Board.

Shakeshaft continues to serve as an Editor of Monthly Notices.

In June 1985, two Open Days were held in which about 1500 members of the general public visited the observatory. In addition about 500 visitors were shown round the observatory under the continuing policy of providing guided tours, by arrangement, for interested groups and societies.

## 9 STAFF

At 1985 October 1, the observatory personnel comprised 27 academic and technical staff, 5 senior research workers, 22 research students, 18 technicians and laboratory assistants, 3 programmers and computing assistants, and 2 secretaries.

Eight research students (D.H.O.Bebbington, T.V.Cawthorne, R.A.Cordey, S.A.Eales, M.A.Faulkner, J.P.Leahy, M.J.Spinks and S.J.Tappin) were approved for Ph.D. degrees during the year.

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