# Distant Radio Galaxies

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## 1. Introduction

We are at present carrying out an ESO Key Programme to find and study distant radio galaxies using a new technique. Here we give a "mid-term" progress report. The Key Programme is based on a method that we developed for optimizing the chances of finding distant radio galaxies. It is based on a correlation that exists between radio spectral index and redshift. Radio sources with the steepest spectra tend to be more luminous and at larger distances than sources having normal spectra.

The direct objectives of our key programme are twofold. First we wish to increase the sample of distant galaxies and investigate the statistics of the population. Secondly, we are studying the detailed properties of the early-epoch radio galaxies in an attempt to understand how they formed and evolved.

## 2. Background

In the late forties, Cygnus A, the second brightest radio source in the sky, was found to be associated with a faint galaxy having a redshift 0.057. This remarkable discovery led to the realization that radio sources are unique cosmological probes. There are three main reasons why radio galaxies are so important for studying the early Universe. First, their radio luminosities are sufficiently large to enable them to be easily detected out to large redshifts. Secondly, most of them also emit intense emission lines which enable their redshifts to be easily measured. Thirdly, unlike quasars, radio galaxies are spatially extended in the optical and infrared.

During the last decade CCDs have revolutionized studies of distant radio galaxies, enabling much fainter galaxies to be imaged and their redshifts to be measured spectroscopically. From the theoretical standpoint, the search for and study of galaxies having redshifts in excess of 2 or 3 became increasingly important as theoretical arguments based on the canonical "cold dark matter" cosmologies indicated that it was during or after the epochs corresponding to these redshifts that the majority of galaxies were formed.

Until a few years ago, it was thought that although radio sources were used to detect distant galaxies, the radio emission could be "forgotten" in subsequent consideration of their optical properties. However, CCD pictures of distant galaxies showed surprising correspondence between the optical and radio structures. The optical and to a lesser extent the infrared emission were found to be preferentially aligned along the radio axes. The optical/radio alignment is present both for the optical emission lines and the continuum.

The fraction of objects which possess ionized gas halos increases dramatically at redshifts greater than about 0.1. The alignment of the halos with the radio emission can be readily explained by interaction of the jets with the interstellar and intergalactic gas. The more vigorous interaction observed at large redshifts implies that distant radio galaxies may have more gas than nearby ones. The ionized gas halos could then be associated with the collapse of an embryo galaxy during its formation.

The second effect to be observed was more surprising. Not only was the line emission (ionized gas) observed to be aligned along the radio axis, but so also was the optical and infrared *continuum* radiation. The continuum alignment seems to set in at a redshift of about 0.6 and about 80% of radio galaxies having redshifts in excess of 1 have radio and optical continuum structures which are approximately aligned.

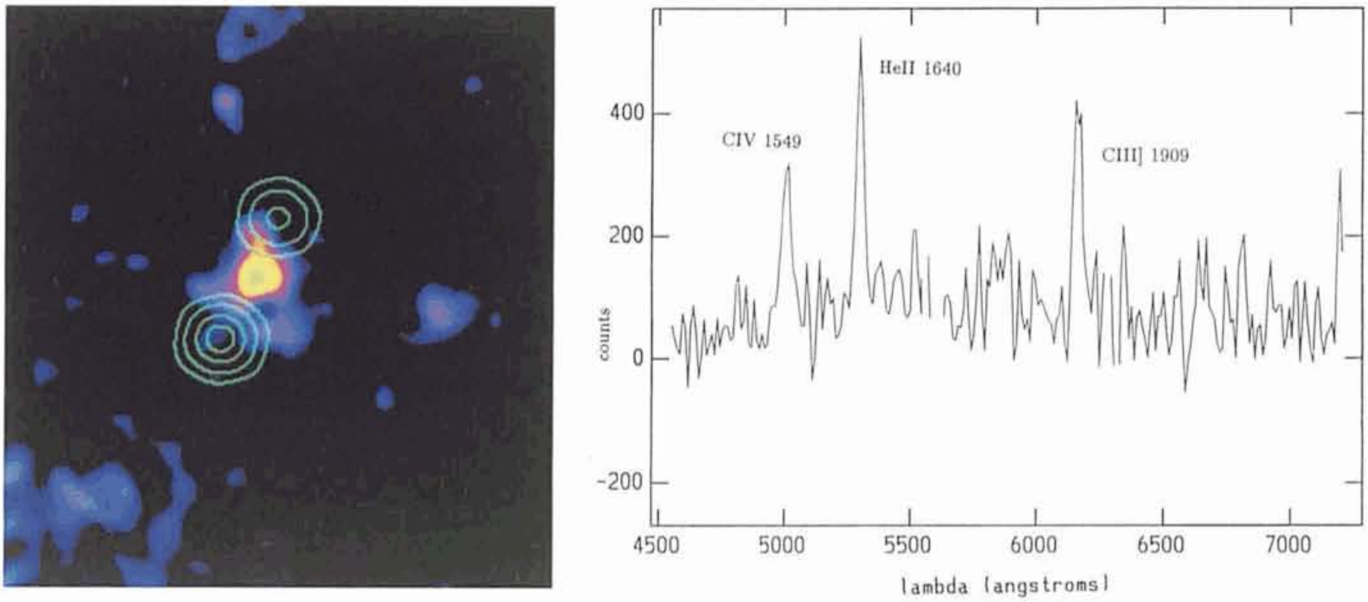

Figure 1: *A z = 2.2 galaxy associated with a Texas radio source. Left is an R-band image (60-minute exposure with the 2.2-m ESO/MPI telescope). The image has a limiting magnitude of ~ 24. The superimposed radio contours are from "snapshot" observations taken with the VLA at 20 cm. The two lobes are separated by 5". Right shows the corresponding optical spectrum (60-minute exposure with EFOSC2 on the NTT).*

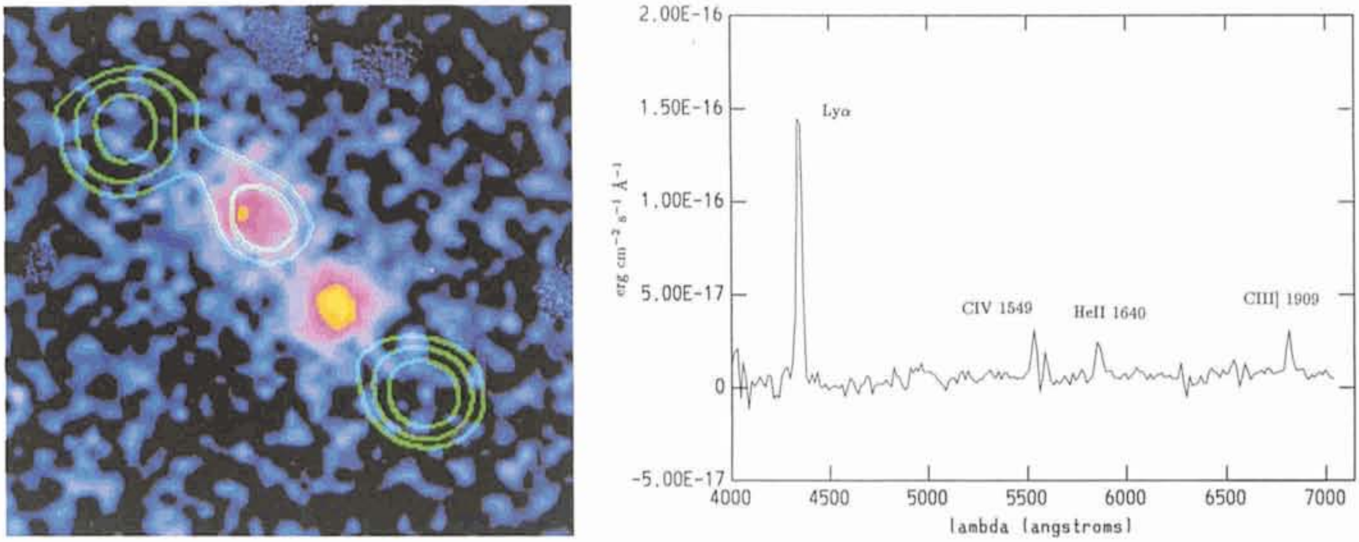

Figure 2: *A z = 2.5 galaxy associated with a Texas radio source. Left is an R-band image (45-minute exposure with 2.2-m ESO/MPI telescope). The image has a limiting magnitude of ~ 24. The superimposed radio contours are from "snapshot" observations taken with the VLA at 20 cm. The two lobes are separated by 12". Note the double optical morphology (see text). Right shows the corresponding optical spectrum (a 45-minute exposure with EFOSC on the 3.6-m telescope).*

Two viable explanations for the optical continuum/radio alignment have been proposed. One possibility is that interaction of the radio source with the intergalactic medium results in the production of a sufficient number of stars to produce the aligned component of the optical continuum emission. An alternative to the starburst picture was prompted by the measurement of appreciable optical polarization in extranuclear emission from the bright aligned radio galaxy 3C 368 by Sperello Alighieri, Bob Fosbury, Clive Tadhunter and Peter Quinn working with EFOSC on the ESO 3.6-m telescope. This led to the suggestion that the aligned optical continuum light that we see from distant radio galaxies is scattered emission from a quasar embedded in the nucleus. Because the quasar shines in a narrow cone along the radio axis, we are unable to see it directly. However, electrons or dust along the radio source see the beam of quasar light and scatter it.

Neither the starburst nor the scattering models by themselves are entirely satisfactory. The presence of polarization means that some scattering must occur, but it cannot be the whole story. In some of the distant galaxies, structures are observed to be aligned with the radio emission, not only at optical wavelengths, but also in the infrared. Using a scattering model it is difficult to produce enough emission to account for the observed aligned luminosities. A composite picture of distant radio galaxies which includes both bursts of star formation and scattering along the radio sources seems most likely. Studies of additional high-redshift galaxies are clearly warranted.

## 3. Finding Distant Galaxies

Barely five years ago, the most distant galaxy known was 3C326.1 with a redshift of 1.8. By concentrating on identifying "ultrasteep spectrum" radio sources, we have since discovered about 25 galaxies having redshift larger than 2, most of these during the ESO Key Programme. At the time of writing, the three galaxies with the largest known redshifts were all found using our ultrasteep spectrum technique.

Finding the high-redshift galaxies has involved a long series of systematic steps at radio and optical wavelengths. After each stage the number of candidates was whittled down. We first made a preliminary selection of several samples of radio sources known to have definite or suspected ultra-steep radio spectra from the Parkes, Molonglo and Texas surveys. Using these initial selection criteria, 650 objects were selected from more than 50,000 sources inspected.

The next stage was to carry out preliminary radio observations with the VLA, and Molonglo Synthesis Telescope (MOST) to find out which of the suspected sources definitely have ultra-steep spectra and to provide radio structural and positional information which can be used for their optical identifications. To this end we made snapshot observations of 550 sources. Using the accurate radio positions, we then sought optical counterparts of the radio sources on Sky Survey plates using the GASP system at the Space Telescope Science Institute in Baltimore. About 80% of the sources in our sample were unidentified.

We then began our ESO observations by making CCD images of ultrasteep spectrum sources that were unidentified on the Sky Survey. With exposure times of typically 3 × 15 minutes through an R-filter on the 2.2-m telescope, we reach limiting magnitudes of about 24. So far we have imaged 170 of the 300 candidates that remained after the preliminary stages of the project had been completed. In order to search for optical identifications, the CCD frames need to be calibrated astrometrically using stars that are present both on the CCD image and on the Sky Survey. All the CCD images have been calibrated and the radio maps have been superimposed. Two examples of our radio/optical overlays are shown in Figures 1 and 2. We selected faint fuzzy optical counterparts on the CCD frames as candidates for optical spectroscopy.

There is a dramatic increase in the space density of quasars between $1.5 > z > 2.8$, the "quasar epoch". Although the detailed behaviour is still uncertain, it appears that the radio galaxy statistics are consistent with a roughly similar behaviour. For objects which are located in the quasar epoch, Lyman $\alpha$ will be observed blueward of 4600 Å. Because in a characteristic spectrum of a radio galaxy Ly $\alpha$ is a factor of 5–10 more luminous than any other observable line, maximum sensitivity in the blue is crucial for measuring the redshifts.

Until recently, there was no CCD on La Silla capable of doing spectroscopy with high quantum efficiency in the blue and low readout noise. The availability of the new Tektronix chip with EFOSC on the 3.6-m telescope has remedied this situation. We used this chip for

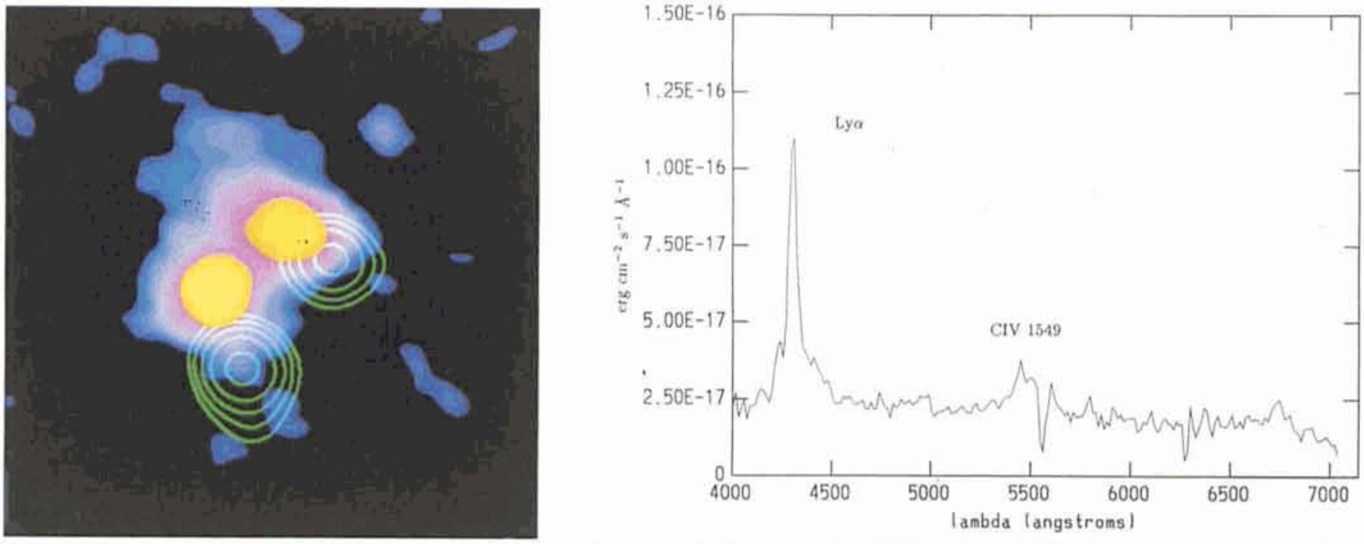

Figure 3: *A second z = 2.5 galaxy associated with a Texas radio source. Left is a 16-minute R-band image (10-minute exposure with EMMI on the NTT). The image has a limiting magnitude of ~ 24. The superimposed radio contours are from "snapshot" observations taken with the VLA at 20 cm. The two lobes are separated by 4". Note the double optical morphology (see text). Right shows the corresponding optical spectrum (60-minute exposure with EFOSC on the 3.6-m telescope).*

the first time on our last observing run and it resulted in a significantly improved detection rate. Taking all the data obtained so far, we have detected emission lines in 30 of the 85 galaxies that we observed spectroscopically. We have determined 30 redshifts of which 23 have z > 1.5 (e.g. see enclosed figures).

The statistics of the photometry and spectroscopy are being analysed together with radio source counts and spectral index distributions and size distributions to place constraints on the evolution of space density of radio galaxies and to compare the redshift dependence of the luminosity function of radio galaxies with relevant data for quasars. In practice such an analysis is complicated and requires considerable care. Well-defined criteria are being developed to allow the identification percentages to be analysed quantitatively, preparatory to constraining the evolution of the luminosity function. Our spectroscopy was done in several separate sessions with different sensitivities and different colour responses. For each of these it is necessary to determine the limiting redshift out to which a standard radio galaxy could have been detected. Account has also to be taken of the radio spectral selection criteria used. A rigorous discussion of the relevant constraints will be undertaken by H. Röttgering in his Ph.D. thesis which is expected to be completed late in 1992.

## 4. Follow-Up Observations

At this stage, we are only about half way through the nominal observing time allocated for the Key Programme. Inevitably, most of the time until now has been devoted to finding new distant radio galaxies. Detecting distant radio galaxies is a prelude to studying their properties. The quasar era at z ~ 2 occurred only about 2 billion years after the Big Bang. Galaxies at larger redshifts are likely to be close to the epoch of their formation. Because they are spatially extended, radio galaxies pro-

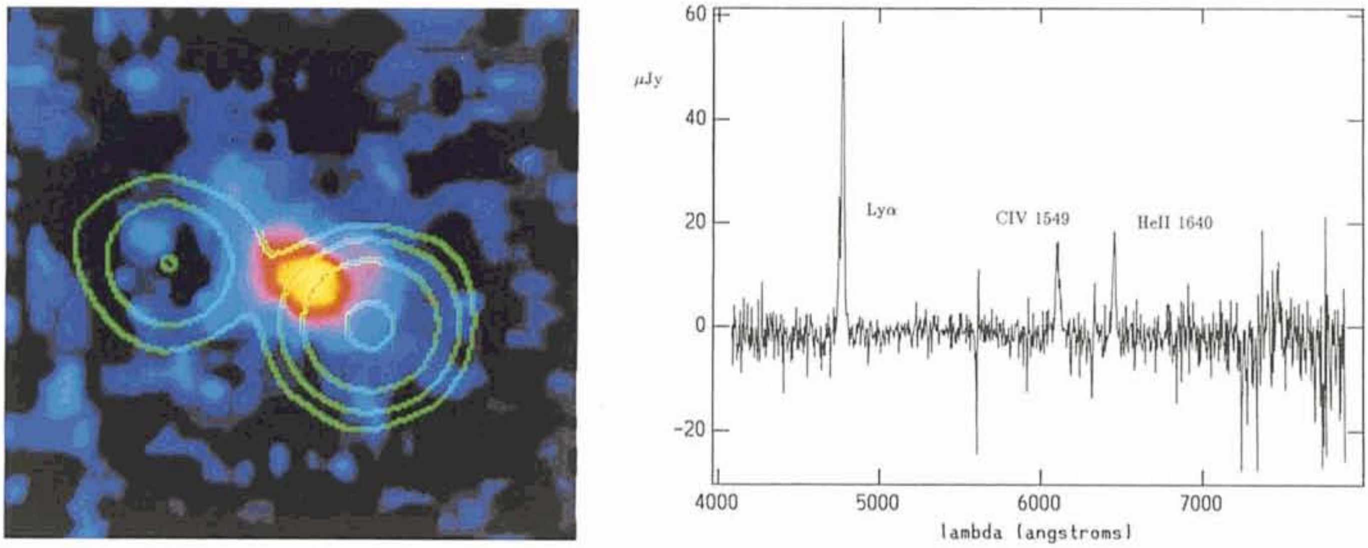

Figure 4: *A z = 2.9 galaxy associated with a Texas radio source. Left is an R-band image (16-minute exposure with EFOSC2 on the NTT telescope). The image has a limiting magnitude of ~ 24. The superimposed radio contours are from "snapshot" observations taken with the VLA at 20 cm. The radio extension is 4". Right shows the corresponding optical spectrum (120-minute exposure with EFOSC2 on the NTT).*

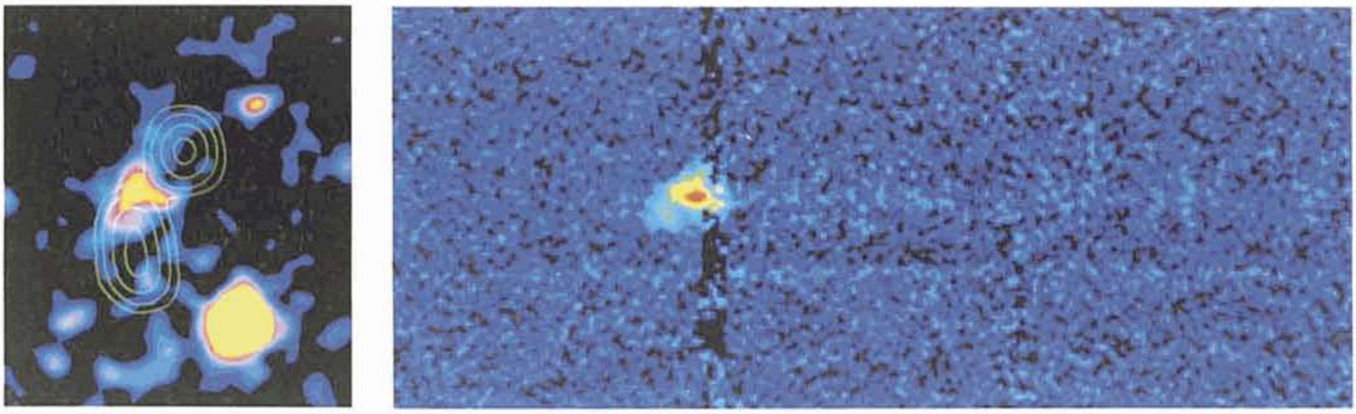

Figure 5: *A galaxy associated with a Texas radio source having a probable redshift of 3.6. Left is an R-band image (45-minute exposure with the 2.2-m ESO/MPI telescope). The image has a limiting magnitude of $\sim 24$. The superimposed radio contours are from "snapshot" observations taken with the VLA at 20 cm. The two lobes are separated by 7″. Right shows the corresponding sky-subtracted 2-dimensional spectrogram (120-minute exposure with EMMI on the NTT). The horizontal axis (wavelength) extend from 5270–6260 Å and the vertical axis is in the spatial direction along the radio axis. One very bright line is observed with a spatial extent of about 8″. The continuum falls off sharply bluewards of the line. The only tenable line identification is Ly$\alpha$ at $z = 3.6$.*

vide unique diagnostics for studying this important stage in history. Since in most cases, the associated emission lines are both bright and extended, they are excellent objects for follow-up spectroscopy as well as narrow-band and broad-band imaging.

Two interesting objects for which we have already done a limited amount of follow-up are shown in Figures 2 and 3. In both cases the following properties are apparent:

(i) A pair of apparently interacting optical objects are aligned along the radio axes.

(ii) Each member of the pair is anomalously bright in R. (Integrated R-magnitudes are 19.7 and 20.8 respectively compared with a typical value of 23 for other radio galaxies at the same redshift ($2 < z < 3$).

(iii) Bright Ly$\alpha$ extends for $> 5''$ over each system.

From these properties we were led to consider the possibility that both objects may be primeval galaxy mergers. However, a study of the extent of the line emission and the colour distributions now leads us to believe that one member of each pair may be a foreground object.

To investigate the probability of chance coincidences in objects of this kind, we are analysing the number vs. magnitude statistics in each of our CCD frames. This study will also provide an important input into discussions of the identification statistics and luminosity function evolution.

We are planning a variety of additional follow-up observations of our highest redshift galaxies. Detailed mapping of the (optical and infrared) spectral energy distributions and analysis of their variations across the galaxies should provide constraints on the optical/radio alignment effect. Models of stellar populations are being refined by Rocca and Guideroni of the Institut d'Astrophysique in Paris for comparison with the spectral energy distributions. The optical data will be complemented by more detailed radio observations with radio arrays, including the Australia Telescope and European and global VLBI networks. A recent discovery by Uson of HI absorption in the radio spectrum of a similar radio galaxy with $z = 3.4$ offers exciting possibilities for using some of our objects for probing neutral gas in the early Universe.

Also, study of the morphologies and kinematics of the ionized gas and the relationship of the line emission to the continuum emission should elucidate the processes responsible for ionizing the gas. The ionized gas halos often extend for more than 100 kpc. The observed nuclear fluxes are insufficient to produce the large emission-line luminosities by photoionization, lending support to the models involving anisotropic photoionization and scattering.

The Key Programme is providing us with a unique dataset of radio galaxies at distances that would have been thought impossible until a few years ago. Studies of these objects from now until deep into the VLT era should provide important information about the early universe.

# European Planetarians Meet at ESO Headquarters

On May 10 and 11, 1992, about 75 Planetarians, representing planetaria from most European countries, gathered at ESO Headquarters in Garching. It was the third meeting of this international group, following earlier ones in Strasbourg (1986) and in Paris (1989). The local arrangements were taken care of by the ESO Information Service, while the scientific programme was organized by Professor Agnes Acker of the Astronomical Observatory at the University in Strasbourg, herself responsible for the planetarium in that city.

The meeting was preceded by a study visit to the Deutsches Museum in München, where the participants were received by the museum staff responsible for the new astronomy exhibition, just opened there (cf. page 21). Under the expert guidance of Drs. Teichmann, Hartl and Wolfschmidt, who first conveyed the new ideas behind the 1000 m$^2$ exhibition, the Planetarians had the opportunity to thoroughly study the numerous displays. Later in the day, they were informed about the new, major planetarium project which will be ready in Munich in 1993.

The actual meeting began at ESO in the late Sunday afternoon with a warm welcome by the Director General, Pro-