RADIO EMISSION OF GALAXIES

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Recent advances in technology made practically the whole electromagnetic spectrum accessible to the scrutiny of astronomers. We can observe galaxies at radio frequencies, in the ultraviolet, the visual, infrared, X-ray and soon in the γ-ray domain. All observations supplement each other. Some observations can be made only in a particular frequency range. The radio observations begin at about 1 MHz and continue through the centimetre wavelengths into the millimetre and more recently into the submillimetre wavelength range (up to 1000 GHz). This vast range of six octaves of frequency calls for different receiving techniques. The emissions that are studied originate from different physical processes. In this review some of the more important recent radio results will be presented and discussed in the light of our knowledge of the evolutionary sequence of galaxies.

At lower radio frequencies (below 1 GHz) most of the observable energy in galaxies originates in the synchrotron emission process. This radio continuum is caused by the braking of relativistic electrons in galactic magnetic fields. The relativistic electrons are believed to originate in supernova events, although more recently additional reacceleration has been considered to be necessary. This nonthermal emission is linearly polarized and hence allows the study of magnetic fields. In this frequency range only some recombination lines of hydrogen have been detected. The bulk of the emission is seen in radio continuum.

Above 1 GHz the thermal (free-free) emission process becomes apparent, particularly in the higher resolution radio maps of the galactic plane. In such maps numerous discrete HII regions are seen as unpolarized radio sources. It is interesting to note that there is a close association between HII regions and supernova remnants in our Galaxy. Also in most external galaxies the radio spectrum in active star forming regions is in general nonthermal -a result of high supernova activity in star forming regions. The formation of massive stars seems to give rise to young supernova remnants. Some extreme blue galaxies, which are highly luminous, are seen with thermal spectra- possibly a stage of evolution where no supernovae have yet occurred. In the radio range above 1 GHz a large number of spectral lines are found. The most famous of these, the HI line at 1.4 GHz, has been used to trace the spiral structure of our Galaxy. Also kinematics of nearby galaxies can be studied using the HI line with both single dish and synthesis telescope observations. The lines of a particular molecule can be observed at numerous frequencies, each corresponding to a particular transition. Also different isotopes of an element can be recognized at different frequencies. In addition to emission lines, absorption can be studied. This myriad of spectral data is used for datailed studies of molecular clouds in our Galaxy. For example, the various NH_3 transitions are good probes of temperature. In external galaxies lines have been detected but so far spectral studies are limited by lack of sensitivity. The study of maser emissions (OH and H_2O) has been more successful. Observations of CO hold great promise. A new generation of millimetre telescopes which are now being commissioned will enhance our ability to probe nearby galaxies in spectral lines. (These telescopes will work up to 300 GHz).

Although practically the whole frequency range of the electromagnetic spectrum has been explored, the data in the submillimetre range (above 300 GHz) are at present rather scanty. So far no large telescopes were available. Also the detector technology is only in its infancy. The observing sites for sumbillimetre observations must be extremely good. In the submillimetre frequency range the stellar radiation is being re-radiated from dust as a continuum. The thermal dust component meets the radio spectrum somewhere near 300 GHz. In the submillimetre range a whole host of molecular and atomic lines are found and will be of great importance in future studies of galaxies.

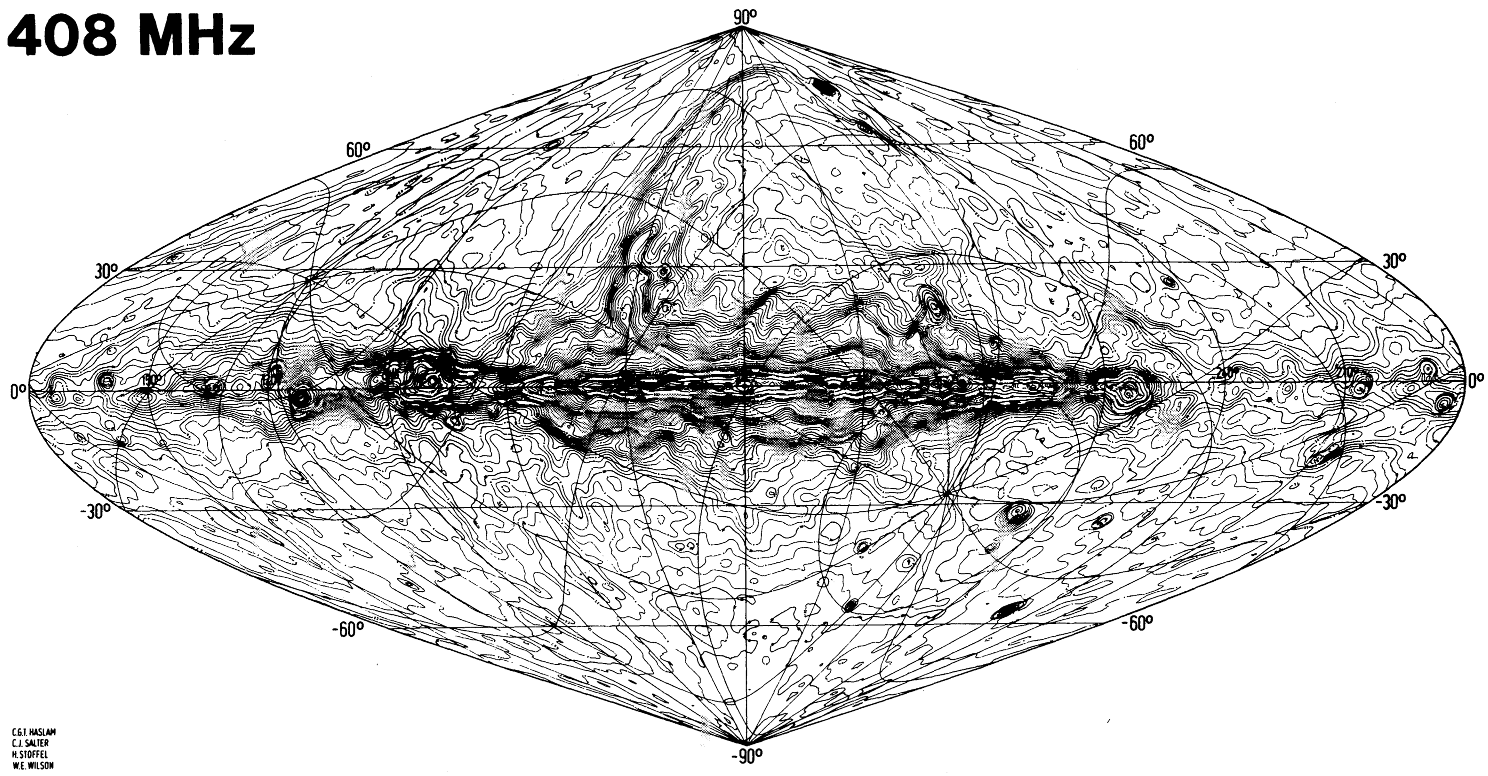

Fig. 1. The 408 MHz survey (C.G.T. Haslam *et al.*, MPIfR). This map shows the dominant nonthermal emission. Along the galactic plane HII regions are superposed on the supernova remnants.

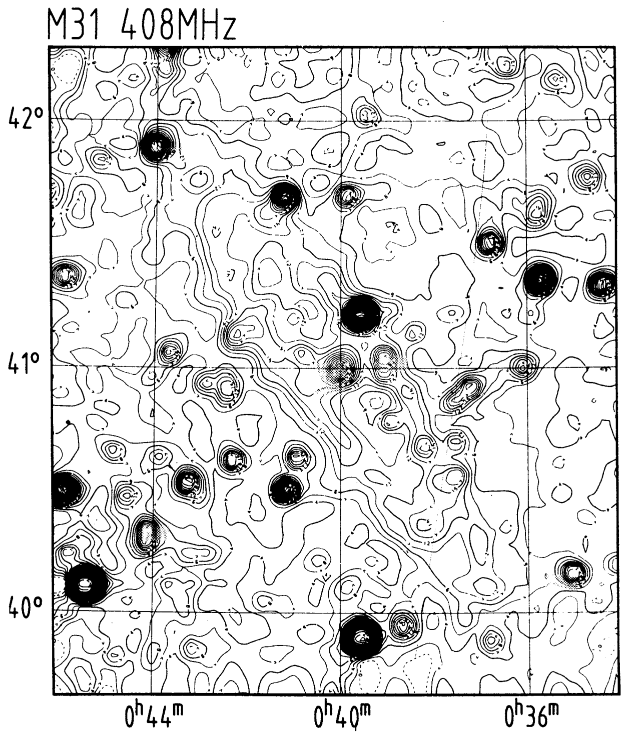

Fig. 2. A 408 MHz map of M31. Nonthermal emission dominates. Our Galaxy would present a similar radio appearance when viewed from Andromeda (R. Grave *et al.*, MPIfR).

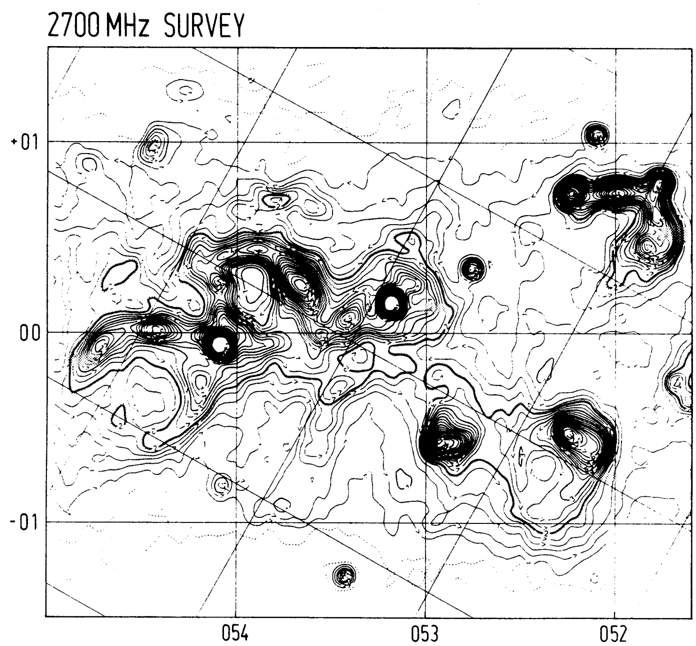

Fig. 3. A section of a 2700 MHz galactic plane survey with an angular resolution of 4.4 arcminutes. Details of SNRs and HII regions are seen. SNRs are linearly polarized. HII regions show a flat spectrum (W. Reich *et al.*, MPIfR).

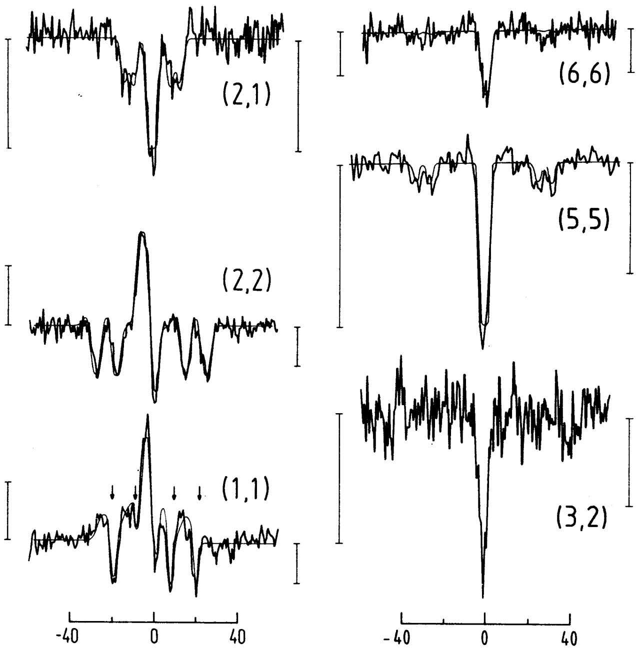

Fig. 4. The (J,K) profiles of Ammonia measured toward the compact HII region in W31. The thick lines are the measured data; the thin lines are the non-linear least squares fits to the data. The arrows in the (1,1) line denote the positions of satellite hyperfine (HF) components of the absorption feature. The vertical bars to the left of each profile represent 1 K, main beam brightness temperature. The vertical bars on the left represent an apparent optical depth (= ln (1- $|T_L|/T_c$) of 0.1. The (3,2) line has no quadrupole hyperfine structure (T.L. Wilson, MPIfR).

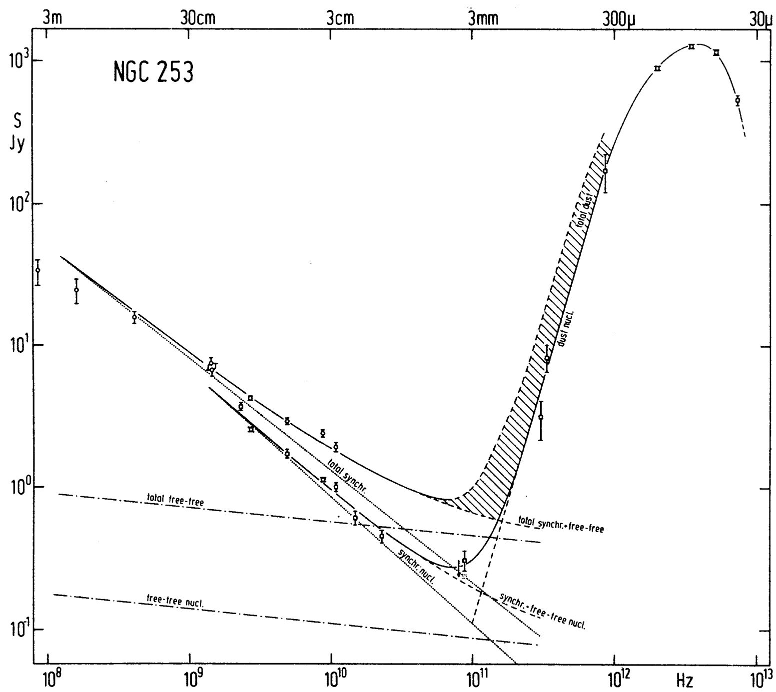

Fig. 5. The spectrum of NGC 253 from 100 MHz to 30 μ. The spectra of the whole galaxy and the nucleus are shown separately (U. Klein, MPIfR).

The study of the Galaxy gives many details but suffers from the lack of reliable distance scales. Large nearby SNRs are seen superimposed on galactic structure with little chance of separation. Even the distances of HII regions are subject to controversy. There has been some success in trying to determine the spiral structure of our Galaxy both in HI line and in radio continuum. By studying nearby galaxies we are at least free from problems of unknown distance. All objects in a galaxy are at least at the same distance. We face, however, problems of angular resolution and sensitivity which have been partially overcome by the new radio telescopes like the 100-m Effelsberg dish, the Westerbork Synthesis Radio Telescope and the Very Large Array.

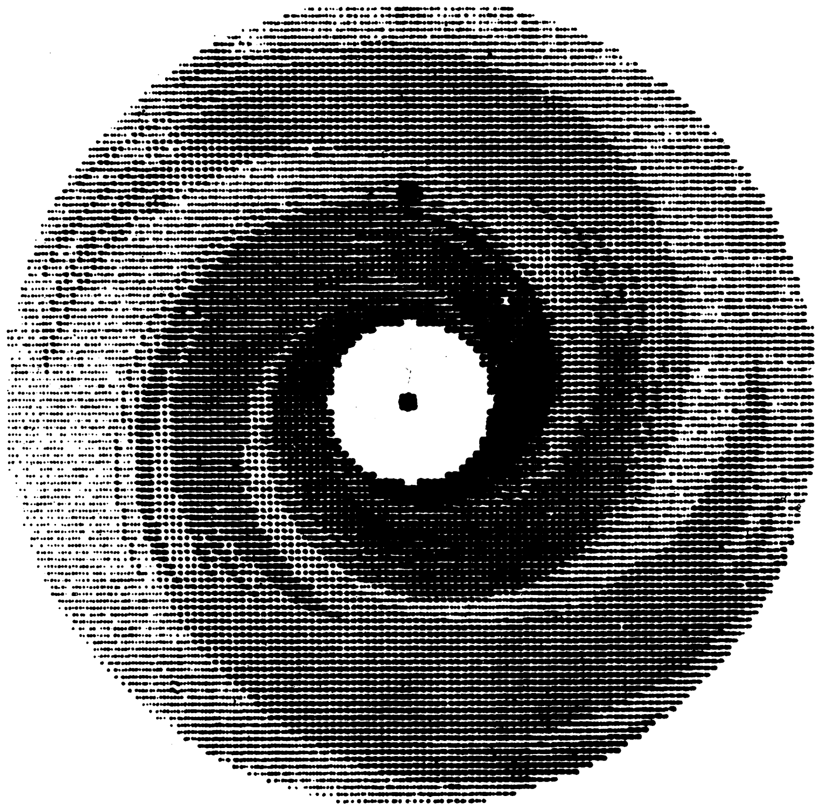

Fig. 6. The deconvolved galactic plane from the 408 MHz survey. The position of the Sun and galactic centre is indicated. The spiral structure is clearly seen in radio continuum (S. Phillips, C.G.T. Haslam *et al.*, University of Durham - MPIfR).

The nearest external galaxies, the Large and Small Magellanic Clouds, are poorly studied at radio frequencies. The reason for this is the lack of large radio telescopes in the southern skies. The radio maps from Parkes, Molonglo and Villa Elisa give us a global picture of the radio continuum and HI line distributions in these irregular galaxies. Studies of star forming regions, particularly of the 30 Doradus complex, with small millimetre telescopes have given us an insight into some details of processes taking place. While radio data is lacking the UV, optical, IR and X-ray studies of the Magellanic Clouds are extending our knowledge of the properties of these objects.

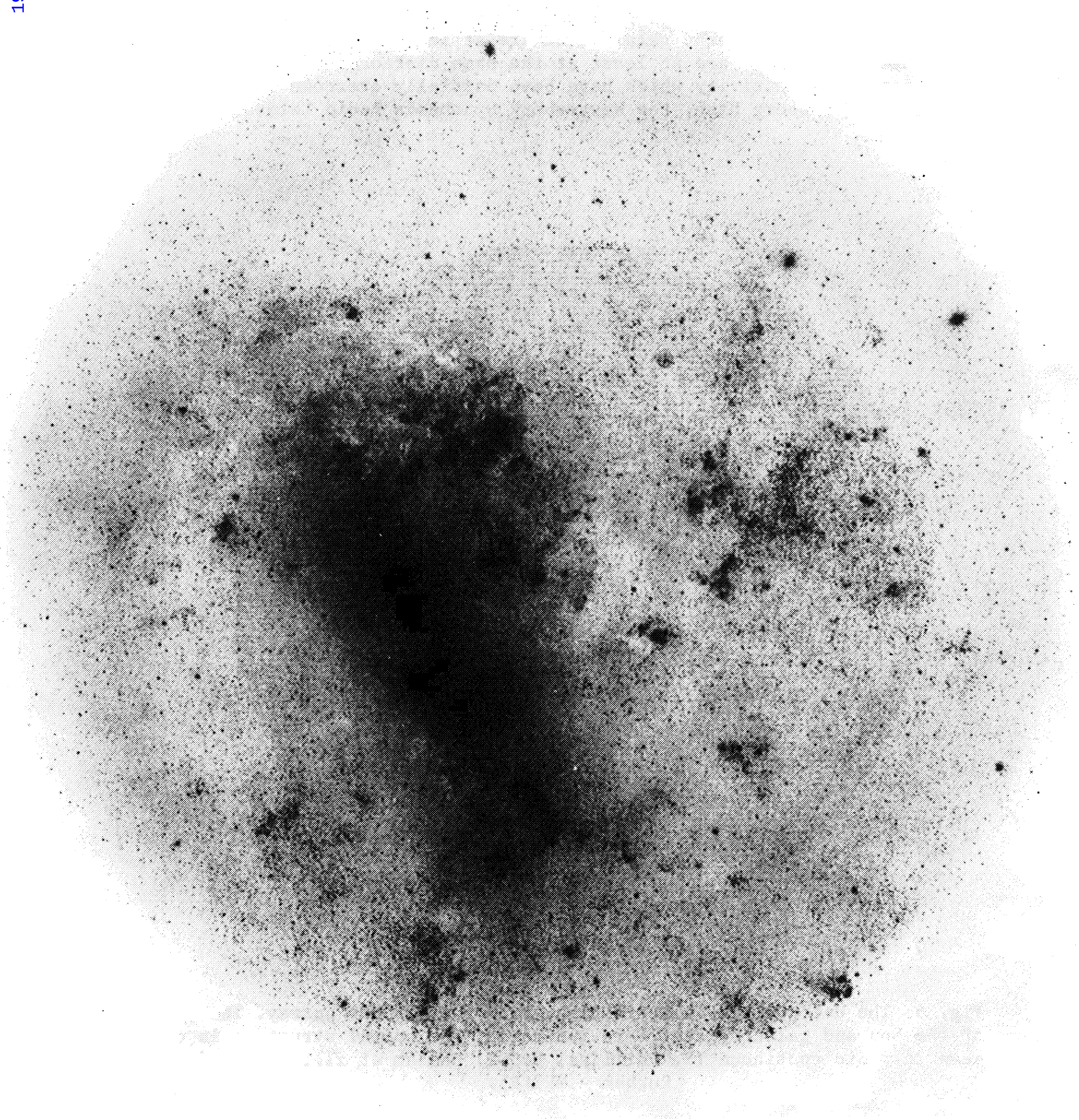

Fig. 7. A 103a0 plate of the Large Magellanic Cloud taken with the Schmidt telescope at Boyden Station (E.H. Geyer, University of Bonn).

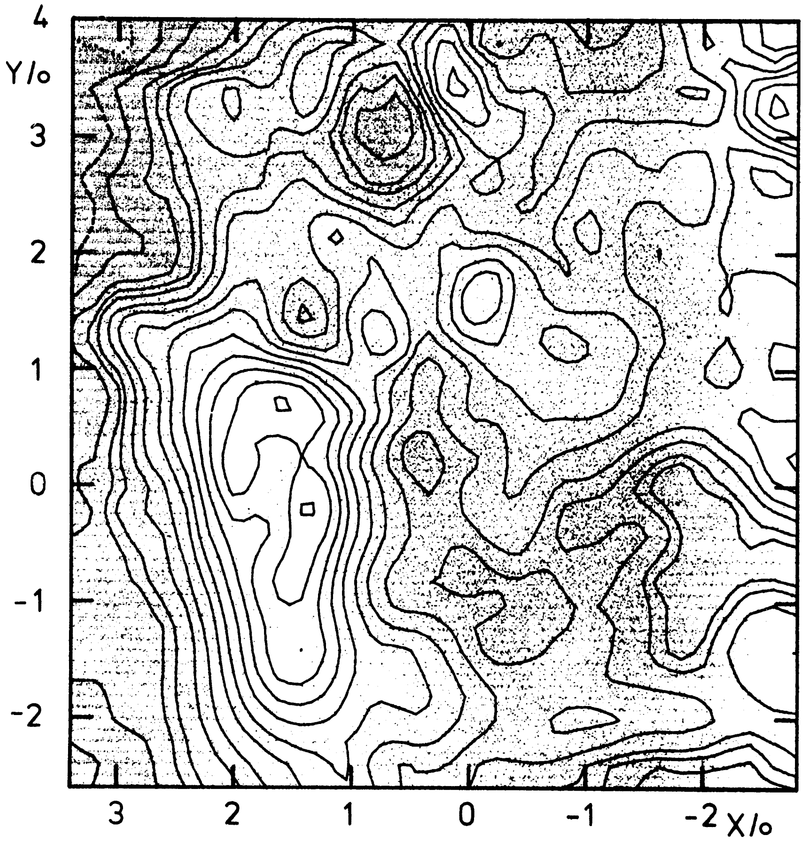

Fig. 8. The distribution of HI in the Large Magellanic Cloud observed with the Parkes Telescope (K. Rohlfs, Bochum University).

The nearest spiral galaxy, the Andromeda Nebula, has been the subject of detailed studies in all frequency ranges. High resolution radio continuum maps have recently become available at 610 MHz, 1.4 GHz and 5 GHz. Linear polarization has been measured at radio frequencies, confirming older optical polarization studies. High resolution HI studies of M31 show details of gas distribution. Balloon flights gave us excellent UV pictures of M31. The newest data on M31 comes from IRAS -showing that like in the radio domain a ring-like structure is present. A few years ago exciting data on the X-ray sources in M31 came from the Einstein Observatory. Molecular detections in M31 are rather sparse. There is some CO, some H_2CO. Other galaxies, notably M82 and NGC 253, are seen to contain numerous molecules.

Other nearby galaxies like M33, IC 342, M101, NGC 6946, M51, etc., have been well studied in radio continuum, in HI and some in CO line. From radio continuum maps at several frequencies the separation of the thermal (free-free) and nonthermal emission is possible. A study of a large sample of nearby galaxies showed that the thermal fraction is less than 40% at 10.6 GHz. Most of the nearby galaxies show well-aligned magnetic fields along the spiral arms. The spectral index of a large sample of galaxies was found to be $\alpha \cong 0.75 \pm 0.1$ ($S \propto \nu^{-\alpha}$). Only extreme blue galaxies like IZw 18 or IIZw 40 showed flat spectra. Surprisingly these blue galaxies are also highly radio luminous. A radio luminosity-colour relation could be established. The distribution of radio continuum can be described in terms of a nucleus-disk-halo model. All galaxies show nuclear emission in radio continuum. The intensity of this emission varies however considerably with no apparent connection to other parameters. The disk emission is dominant in most galaxies and seems to be unconnected with nuclear activity. The disk radio continuum is most intense in galaxies with well defined spiral structure like M51. These galaxies also have the best aligned magnetic fields. The halo emission, that emission which is

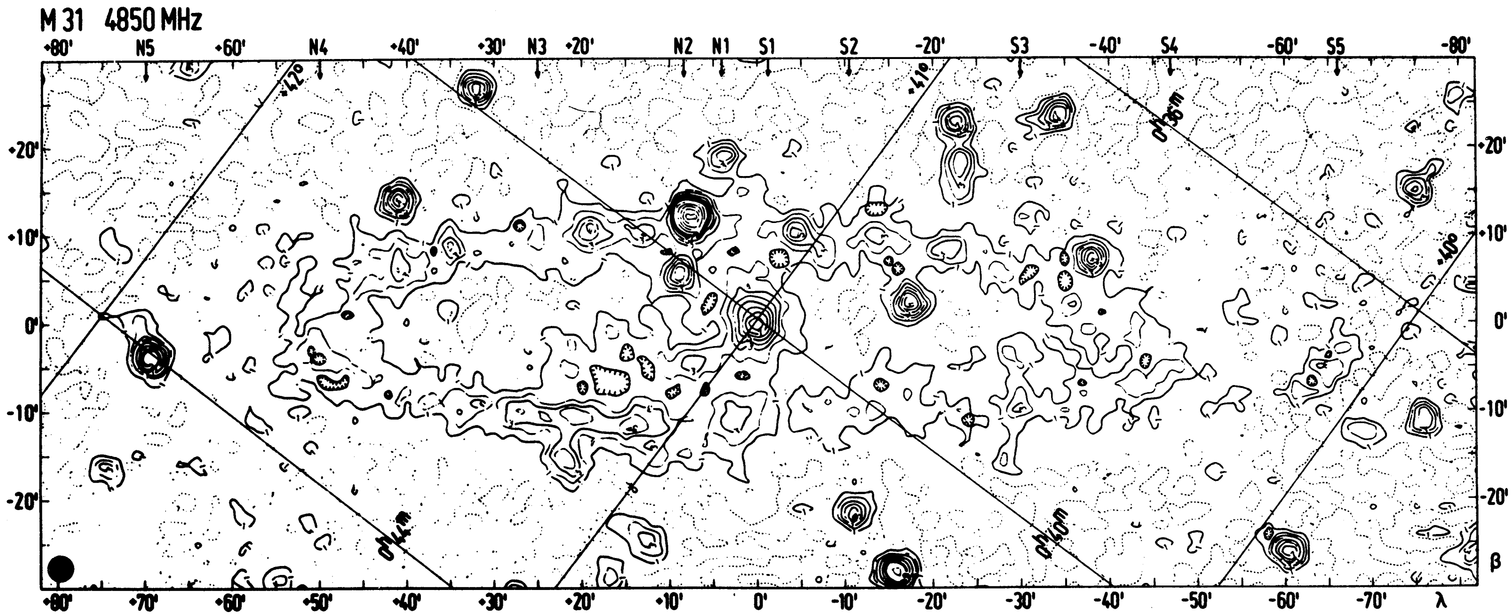

Fig. 9. A 4.8 GHz (λ6 cm) map of M31. At this frequency some 40% of the radio continuum emission is thermal (E. Berkhuijsen *et al.*, MPIfR).

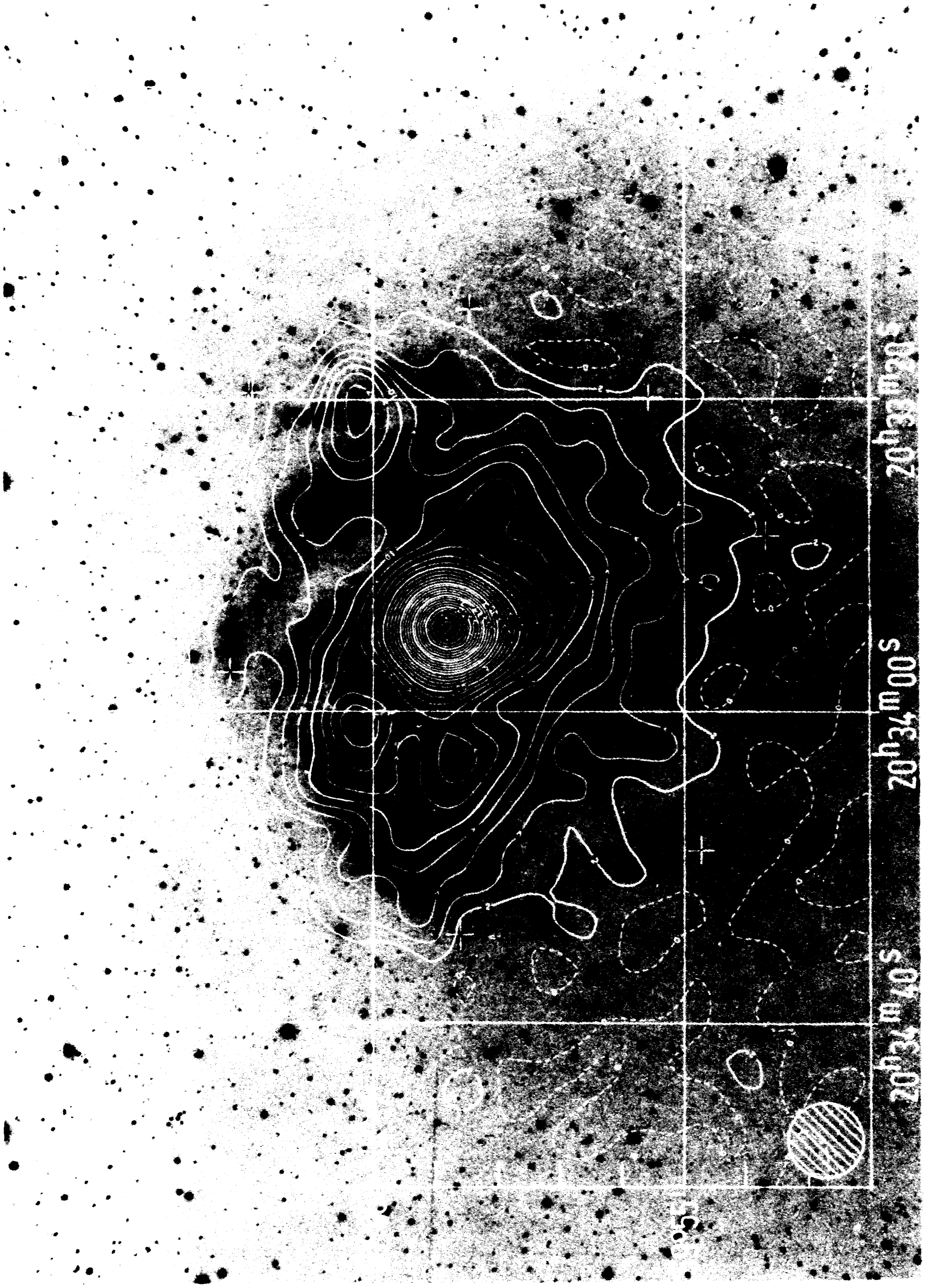

Fig. 10. A 10.7 GHz (λ2.8 cm) map of NGC 6946. When combined with maps of similar angular resolution at 610 MHz the spectral index distribution leads to a separation of the thermal and nonthermal emission (U. Klein *et al.*, MPIfR).

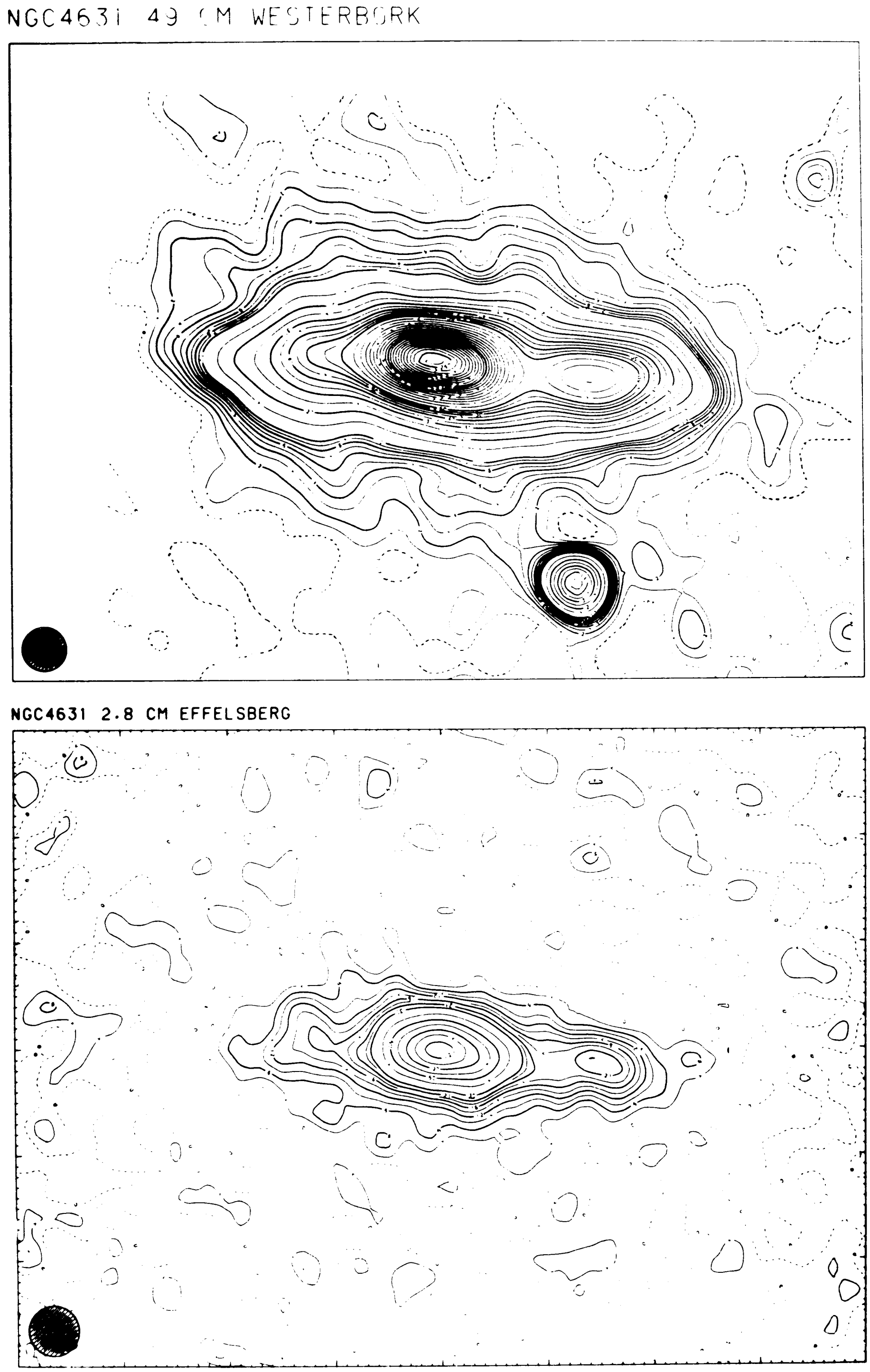

Fig. 11. Maps of the edge-on galaxy NGC 4631 at 610 MHz (λ46 cm) and 10.7 GHz (λ2.8 cm) with similar beams. A halo at the lower frequency is apparent (W. Werner *et al.*, MPIfR).

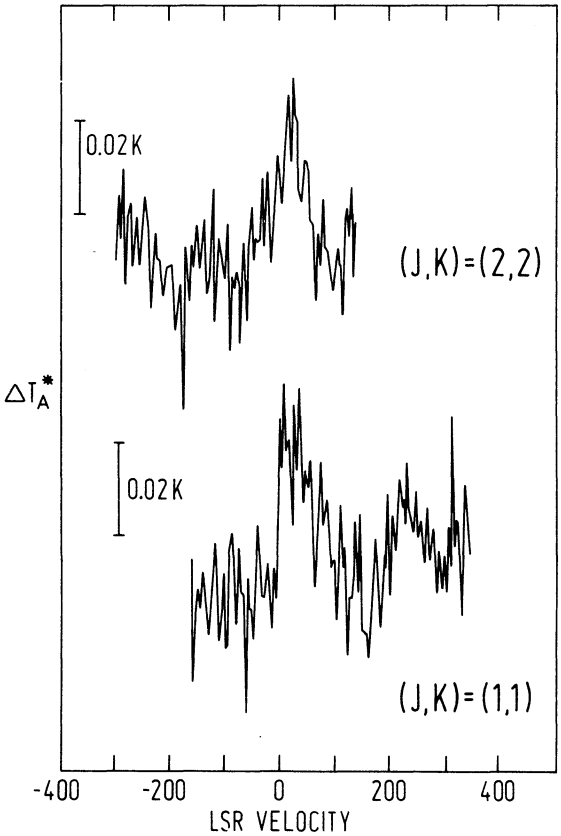

Fig. 12. The (J,K) = (1,1) and (2,2) spectra of NH_3 towards the nucleus of IC 342. The beam diluted brightness temperature is shown (P. Ho, K. Ruf *et al.*, Harvard - MPIfR).

seen away from the disk, is seen in some galaxies. Radio emission in the halo is best studied in edge-on galaxies like NGC 4631, NGC 891, etc.

The HI studies of nearby galaxies have given us vast new data on the kinematics of these objects. At first single dish telescopes were used to study the HI distributions in galaxies. The speed and the angular resolution of the present large synthesis arrays which can map in HI have all but surpassed the classical optical methods. Only in nuclei of galaxies optical spectroscopy competes with the radio methods. Rotational curves of galaxies could be traced out to 30 kpc and more in some cases. Many galaxies show a minimum of HI in the nucleus -a result of conversion of HI gas into stars? A large sample of galaxies can be studied in the HI line.

Molecular line studies are limited at present to rather a small sample of nearby objects. The OH molecule was the first molecule to be detected in an external galaxy. Detections of H_2CO and CO soon followed. In fact CO seems to be very widely distributed and will with the advent of the larger millimetre telescopes play an important role in galactic studies. H_2O masers have been observed as well as HCN, NH_3, HCO^+ and CH. In many galaxies the maximum of line emission comes from the nuclear area. Some show no emission in the nucleus but in an annular ring. Isolated emission regions, in particular giant HII regions, are often associated with some molecular emissions. A better understanding of molecular line emission awaits new data.

Intense Far-Infrared (FIR) continuum emission was detected from the centres of some nearby galaxies (e.g. M82, NGC 253, M51, NGC 1068). This emission reached its maximum near 100 µm and was interpreted to be due to dust. The presently accepted mechanism is the re-radiation of the optical light by the grains which are at 20 - 50 °K temperature. This data has been substantiated by observations from the Kuiper Airborne Observatory and more recently by the IRAS satellite. So far mainly nuclei of galaxies were studied. Some maps of galaxies, in particular of M51 and NGC 6946, at 170 µm have become available and can be compared with the radio data. Exciting new possibilities of interpretation emerge in this frequency range. In addition to the radio continuum, the submillimetre range is full of atomic and molecular lines. The sensitivity of present detectors is such that substantial data on lines in galaxies should become available in the near future.

Radio studies of galaxies gave us a great amount of new data. These data can be used in conjunction with observations in other frequency domains to better understand the evolution of galaxies.

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