Mapping of Galaxies at High Radio Frequencies

R. Wielebinski

Professional astronomers are sometimes asked the question of whether observations with radio telescopes are better than the "old-fashioned" optical observations? The answer is of course that they are equally valid: to understand the objects in the Universe, we must observe them over the widest possible spectral range. For this purpose, short-wavelength observations are now carried out from spacecraft, and in the other end of the spectrum we rely upon the ingenuity of the radio astronomers with their giant antennas. In this review, Dr. Richard Wielebinski of the Max Planck Institute for Radioastronomy in Bonn, FRG, gives examples of the important interaction between optical and radio observations for the study of nearby galaxies.

The detailed study of the distribution of the radio continuum emission of "normal" galaxies began only ten years ago, when G. G. Pooley published a map of the Andromeda nebula (M 31) made at 408 MHz. This map showed for the first time details of the spiral structure at radio frequencies. Until that time no single-dish radio telescope had sufficient angular resolution and no synthesis array the necessary brightness sensitivity to be able to map nearby normal galaxies. A typical angular resolution required for the largest objects is a few minutes of arc, while tens of seconds of arc resolution allow us to study numerous smaller galaxies. A number of presently operating synthesis arrays have this resolution, and have been used to map galaxies, particularly at lower radio frequencies. The surface brightness of the radio continuum emission of normal galaxies is low, typically a few degrees K at 408 MHz, but dropping rapidly to a few mK at 4 800 MHz. (The temperature spectral index β is typically $\sim$ 3.0 for galaxies in this frequency range — $T \propto \nu^{-\beta}$.) For such sensitive measurements the large collecting area of a single dish, like the 100 m Effelsberg radio telescope, is ideal. To map galaxies at frequencies above 5 GHz, where weather effects seriously hamper observations, the development of new techniques was necessary to allow studies to be made in this important frequency range.

Thermal and Nonthermal Emission

To understand the importance of mapping of galaxies at high frequencies, a short summary of the emission processes which produce the radio continuum in our galaxy should be made. Along the galactic plane we have a narrow band of discrete H II regions with thermal (flat) spectrum. The brightest of these H II regions placed at the distance of 1 Mpc would be barely detectable as individual sources, but the integrated effect should certainly be the dominant emission at the highest radio frequencies. A somewhat broader distribution of nonthermal supernova remnants (with steep spectrum) is found along the galactic plane in the Galaxy. The strongest of these SNR's should be easily detected at a distance of even 4 Mpc as individual radio sources. The supernova events are known to produce pulsars, and they as well release energy in the form of relativistic particles. These electrons in turn produce diffuse nonthermal emission which is linearly polarized. The measurement of the linear polarization should enable us furthermore to study the magnetic fields in the galaxies.

Sensitive measurements of the emission above the plane, particularly in edge-on galaxies, allow us to study the diffusion (or convection) of relativistic particles from the sites of their formation into the magnetic fields of a possible "halo". The study of the diffuse thermal emission, known to exist in our galaxy from the absorption of low frequency continuum emission, could be tackled once a careful separation of the thermal/nonthermal emission is made. To separate all these effects radio maps at many frequencies are required. These radio results, combined with various other observations, should enable us to understand the energy balance of galaxies.

Mapping the Spectral Indices and Magnetic Fields

The 100 m radio telescope of the Max-Planck-Institut für Radioastronomie has been used to map nearby galaxies at a number of frequencies from 840 MHz to 23 GHz. At first a λ 11 cm (2.7 GHz) map of M 31 was made with r. m. s. noise of 3 mK. Measurements with such sensitivity were never made before and were only possible due to the combination of the excellent telescope and the highly stable, low-noise receiver. The data obtained for M 31 were studied in detail by E. Berkhuijsen, particularly for correlations between radio continuum and the various constituents like H II regions, OB associations, supernova remnants, H I gas, blue light, etc. Similar investigations have been made on the basis of λ 11 cm and λ 6 cm maps of M 33. In M 33 the emergence of the thermal emission as the dominant constituent, even below 4.8 GHz, is evident.

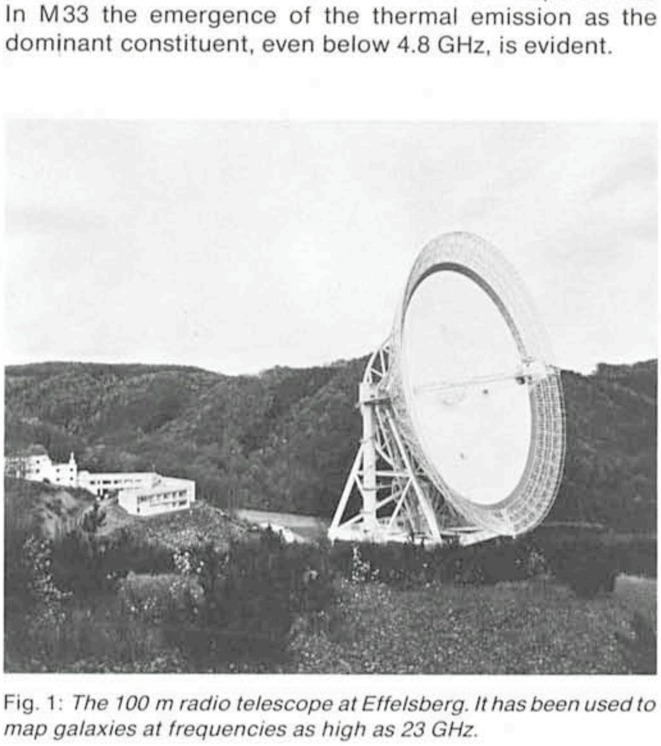

Fig. 1: *The 100 m radio telescope at Effelsberg. It has been used to map galaxies at frequencies as high as 23 GHz.*

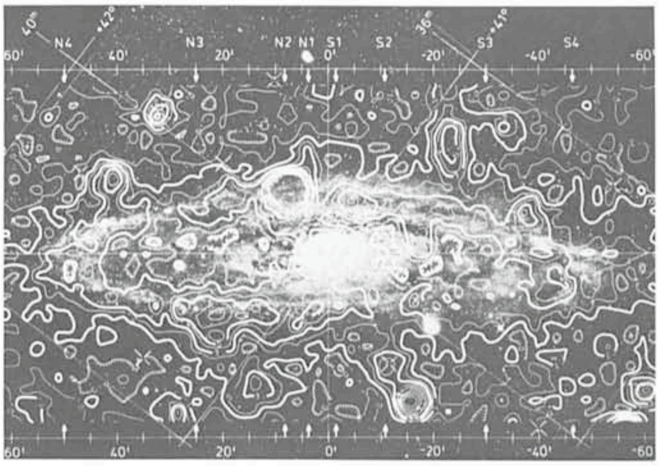

Fig. 2: *M31—An overlay of radio contours onto a Lick Observatory photograph. 2695 MHz (λ 11.1 cm), 4!7 beam (Berkhuijsen and Wielebinski).*

Studies of IC 342, M 81, M 51 and, more recently, M 82 at frequencies as high as 23 GHz have aimed at an accurate thermal/nonthermal separation. To map galaxies at these high frequencies, without being subject to base-level variations due to perturbations from atmospheric thermal emission, the technique of beam switching was extended from point sources to extended objects by D.T. Emerson, U. Klein and G. Haslam. It now appears possible to map galaxies with 1 mK r.m.s. noise and a resolution of 1.2 arc min at 10.6 GHz (λ 2.8 cm). In the near future maps with ~ 30 arc sec resolution at 32 GHz (λ 9.6 mm) should be possible. Such maps, when combined with similar resolution maps made, for example, with the Westerbork Synthesis Radio Telescope in the Netherlands at 610 or 1 420 MHz, or with the Cambridge 150 MHz telescope in England, can give us excellent spectral index distribution maps and hence thermal/nonthermal ratios in a number of nearby galaxies.

Maps of linear polarization of M31 and M33 have been made by R. Beck at 2.7 GHz with 4.4 arc min angular resolution. These observations have shown that the nonthermal emission is generated in magnetic fields which are ordered on scales of kpc. The degree of polarization is high, up to 40 % in some areas. As yet no maps at other frequencies have been made, but in the south-preceding arm of M31 there seems to be very little Faraday rotation. The well-aligned "E" vectors imply that there is a large-scale magnetic field of some 5 μG along this spiral arm. Observations now planned at other frequencies should give details of the magnetic fields and of the electron densities in the spiral arms.

Galaxy Halos

Nonthermal emission from the Galaxy was the first radio-astronomical observation made some 40 years ago. Studies of nonthermal emission in our galaxy has led to

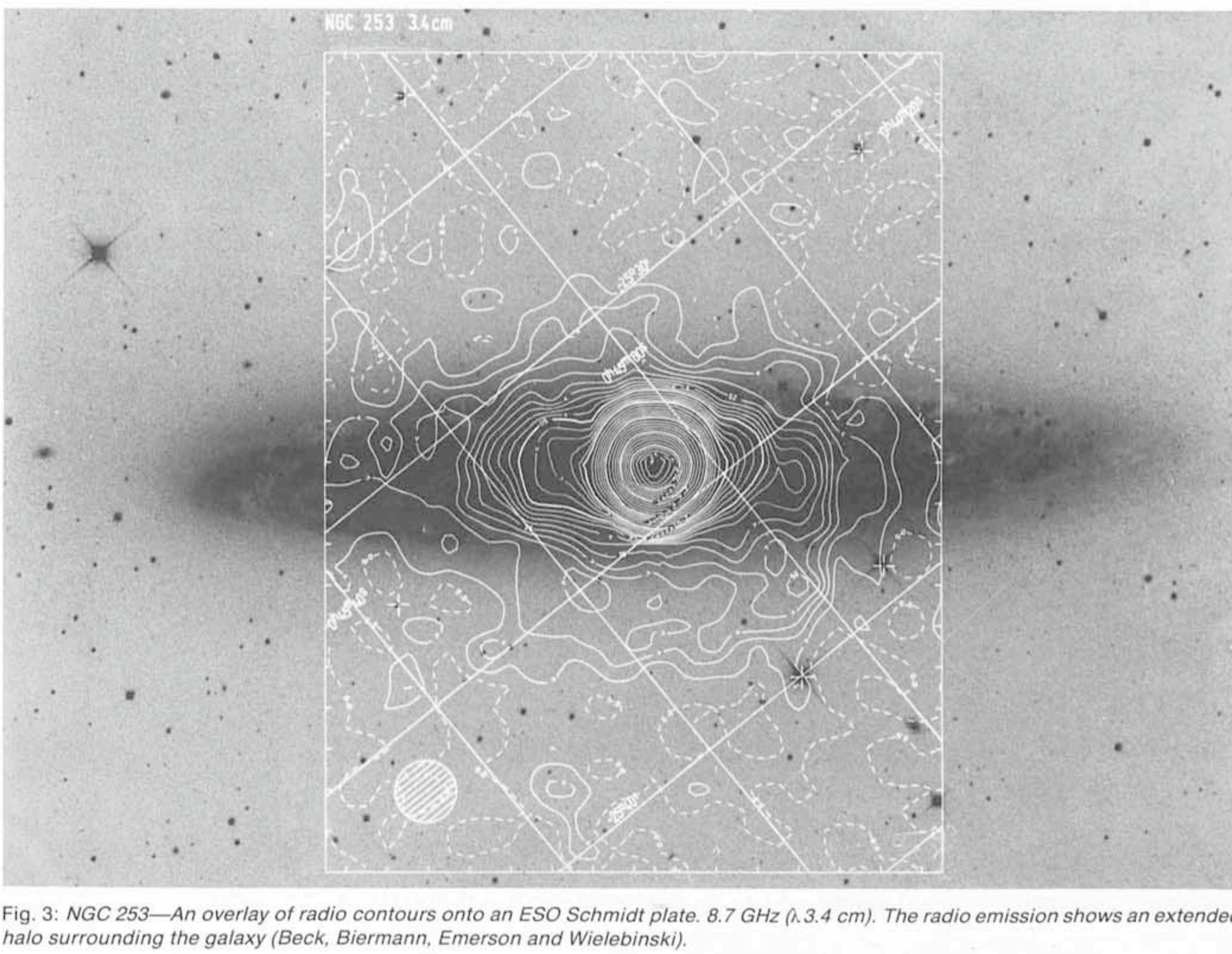

Fig. 3: *NGC 253—An overlay of radio contours onto an ESO Schmidt plate. 8.7 GHz (λ 3.4 cm). The radio emission shows an extended halo surrounding the galaxy (Beck, Biermann, Emerson and Wielebinski).*

a long-standing controversy about the existence of an electron halo. If cosmic rays are to be contained in the Galaxy, a rather strong electron halo is expected. The refinement of measuring techniques over the last 20 years has led radio astronomers to conclude that any such large scale component surrounding the galaxy must be weak. Also the experimental evidence indicates that the spectral index of the radio continuum emission at high distances above the galactic plane is steeper than the spectral index near the plane.

Observations of edge-on or nearly edge-on galaxies offer the best opportunity to study the halo phenomenon. An analysis of 408 MHz observations led R. Wielebinski to conclude that any halo around M31 is weaker than that surrounding the Galaxy. Further studies of the halo of M31 using the 100 m telescope were made recently at the "low" frequency of 842 MHz by R. Gräve et al. Other edge-on galaxies mapped were NGC 891 and NGC 4631. The only high frequency halo so far found was at 8.6 GHz in NGC 253 (R. Beck et al.). This observation implies a young population of relativistic electrons and this may be due to the high nuclear activity seen in NGC 253. The relation between nuclear source and radio emission in the disk is unclear at present. Studies of the nuclei of galaxies, particularly with the highest angular resolution of the VLBI technique, should tell us something about these relations and hence about the energy production in galaxies.

What Comes Next?

Future instrumental developments necessary in this field of research are now becoming apparent. Single-dish maps at the highest frequencies will be able to provide information on the thermal emission distribution in nearby galaxies. At present, to map a larger galaxy at 10.6 GHz down to the confusion level of the telescope would take ~ 1,000 hours. Developments which would speed up the observing, such as use of multi-beam receiver systems, are highly desirable. Aperture synthesis telescope maps at lower frequencies require the filling of the missing spacings. If this is not done, the extended structure is lost and the resulting map unusable for detailed studies. Combination of synthesis arrays and single-dish maps would give data which could be used in detailed spectral studies. The improvement in VLBI sensitivity by the use of a broader bandwidth should enable detailed studies of a larger number of nuclei of galaxies.

Studies of the radio continuum distribution in galaxies require parallel information from all other astronomical observation modes. For the investigation of the thermal content Hα-data are required. To study the relation of radio continuum to the density wave theory, high resolution H I studies of the same galaxies are needed. The halo of our galaxy can be investigated either in radio continuum or in γ-ray observations. Molecular line studies of normal galaxies have so far been limited either to nuclei or to extremely large H II regions. The advent of new techniques in all fields of astronomy and their application to studies of nearby galaxies will certainly bring us nearer to understanding the workings of these beautiful beings.

General References

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δ Crucis is Variable!

E. W. Elst

During a recent visit to La Silla, Dr. Eric W. Elst of the Royal Observatory at Uccle, Belgium, discovered that one of the stars in the Southern Cross is variable. So are many other stars, but the present case is particularly interesting because the maximum amplitude in the lightcurve is only $0^m\!.006$! The discovery is a powerful demonstration of the quality of the La Silla site and a tribute to the Bochum 61 cm telescope and its photometer.

Although the bright, southern star δ Crucis ($V = 2^m\!.8$) has been observed many times during the past, its variability has remained undiscovered until now. Due to the high precision of the Bochum 61 cm photometric system and extremely good weather conditions, it was possible, during my last stay at ESO in February 1979, to detect a short-periodic light variation of δ Crucis, with an amplitude of only $0^m\!.006$!

Fig. 1: *The Southern Cross above La Silla. δ Crucis is indicated. Photographed by ESO photographer B. Dumoulin in 1977. The two bright stars below are α and β Centauri.*