Radio continuum emission from the nuclear region of M31: evidence for a nuclear radio spiral

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Summary

We present new radio continuum observations of the nuclear region of M31 over a wide frequency range. Our highest resolution map, at 21 cm, shows evidence for spiral-like filaments associated with recently discovered features in the ionized gas distribution (Jacoby et al., 1985). These filaments have sizes of several hundred pc and probably do not lie in the plane of M31. We discuss the spectrum of the whole nuclear complex from 73.5 cm (408 MHz) down to 2.8 cm (10.7 GHz). Although the bulk of the emission is nonthermal with spectral index $-0.75 \pm 0.05$ a possible thermal contribution of 25%–50% at 2.8 cm is predicted from the optical emission line gas. If the gas is shock ionized the thermal radio flux may be lower. The total radio emission can be caused by supernova remnants but also by these large scale shocks. The processes occurring in the nucleus of M31 seem to be very similar to, though less violent than, those recently discovered in other spirals.

Key words: galaxies: M31 - nucleus - radio continuum synchrotron radiation - thermal emission

1. Introduction

The nuclear region of M31* differs in several respects from the nucleus of our Galaxy. In particular there is no evidence for recent star formation in the M31 nucleus and the overall gas content is low. Recently, Jacoby et al. (1985, hereafter JFC) have shown that the ionized gas shows an interesting spiral-like morphology with a size of several hundred parsecs. In this paper we will discuss the radio continuum emission from the nucleus of M31.

Recent radio continuum observations of the nuclear region of M31 have been presented by Hjellming and Smarr (1982) and Berkhuijsen et al. (1983). The emission comes from a roughly spherical region with a radius of about five arcmin corresponding to one kpc at a distance of 690 kpc (Baade and Swope, 1963). Hjellming and Smarr (1982, HS hereafter) concluded that the surface brightness as a function of distance from the centre drops exponentially. Some condensations are visible superposed on a smooth extended source (van der Kruit, 1972; HS) but Crane et al. (1981) found that at a few arcseconds resolution all of the emission is completely resolved. Thus M31 has no counterpart to the compact radio source in the Galactic Centre (e.g. Lo et al., 1985) The average brightness temperature of the nuclear emission in M31 is 0.6 K which is more than an order of magnitude lower than the brightness temperature of the Galactic nucleus.

We have used recent WSRT measurements, new measurements obtained with the 100-m telescope at Effelsberg, and published data to study the structure and the spectrum of the nuclear emission. In section 2 we give a brief description of the relevant data. Section 3 deals with the properties of the nuclear complex and section 4 with the origin of the radio emission. In section 5 we discuss the results.

2. Observations

2.1 The Westerbork data

We have studied the nuclear radio continuum emission at 610 MHz (49 cm) and at 1412 MHz (21 cm) using two recently completed surveys of M31 with the WSRT (Bystedt et al., 1984; Walterbos et al., 1985). Full details of the calibration and reduction procedures can be found there. The 610 MHz map has a resolution of 54"x82" (raddcs) and a sensitivity of 0.95 mJy/beam. We have multiplied this map with a factor 1.02 to bring the fluxes on the calibration scale of Baars et al. (1977). At 1412 MHz the resolution is 23"x35" and the sensitivity 0.17 mJy/beam. These data were already on the correct calibration scale. For both maps 1 mJy/beam is equivalent to 0.83 K T_b which is the standard value for a full synthesis.

Figure 1 shows the full resolution 21-cm map of the nuclear area of M31. One of the most conspicuous features is the triple radio source NE of the nucleus.

* Note: In this paper we will use the words 'nuclear region', 'nucleus' etc. to indicate a roughly spherical region of 1 kpc radius, not the inner few parsecs.

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Figure 1. Map of the radio continuum emission from the nuclear region of M31 at a wavelength of 21 cm. The beam size is 23"x35" (indicated in the right hand corner). The white + sign indicates the position of the optical nucleus (trace) and the black cross the position of a supernova remnant (see section 2.7). Contour levels are at 0.5, 0.6, 1.2, 1.9, 2.6, 4.2, 6.2, 9.4, and 15.5.

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2.2 The Effelsberg data

A 5' wide strip along the minor axis of M31 has been mapped with the 100-m Effelsberg telescope at 10.7 GHz (2.8 cm). The receiver system, the observational method, and the data reduction procedure have been described by Klein and Emerson (1981). The original resolution was 71" and the sensitivity reached in areas close to the nucleus of M31 was 0.8 mJy/beam, corresponding to 1.6 mK Tb. A full account of these observations will be given by Gräve et al. (in prep.). Figure 3c shows the central part of the map smoothed to 90" resolution to improve the signal-to-noise ratio. The dashed lines, which indicate the observed region, show that the nucleus was not completely covered. The apparently smaller size of the source in figure 3c, compared to figures 3a and 3b, is therefore not real.

3. Properties of the nuclear complex
3.1 Morphology

Figure 2a shows the central part of the 21-cm full resolution image of the nucleus. The continuum emission can be separated into roughly three components: a smooth extended component, unresolved sources, and resolved fine scale structure. Most of the unresolved condensations have compact counterparts at 12" resolution (see 6-cm map from HS) but all of them are resolved at 2" (Crane et al., 1981). We have marked the condensations which have 6-cm counterparts with a cross. For some of them we could determine a 21-cm flux; comparison with unpublished 6-cm VLA data (Van der Hulst, priv. comm.) shows that their spectra are nonthermal (spectral indices between -0.5 and -1.0).

Some of the structure in the 21-cm map has no clear counterpart at 6 cm, probably because the emission is too extended. In particular, there is an extension to the north, bending to the northwest at 1.2 arcmin from the optical centre, and an extension to the south, bending to the southeast at 1.5 arcmin from the centre. Only the beginning of these features can be seen in the 6-cm map of HS. The radio structures coincide with spiral-like features in the ionized gas distribution which have recently been discovered by JFC. Figure 2b shows the filaments as seen in H-alpha+[NII]. The orientation of the filaments indicates that they probably don't lie in the plane of the galaxy (see also JFC). In fact, from the available data it is not clear whether the filaments lie in a plane or have a 3-dimensional distribution. Large radio filaments extending out of the plane have also been found in the Galactic Centre (Sofue and Handa, 1984). Velocity measurements by Rubin and Ford (1971) and Dehavreng and Pellet (1975) indicate that the ionized gas rotates around the nucleus with velocities up to 200 km/s at 400 po. Severe velocity deviations up to 100 km/s are present though. The maximum rotational velocity of the gas is higher than that of the stars by about 100 km/s (McElroy, 1983).

3.2 Spectrum

In figure 3 we show maps at 49, 21 and 2.8 cm with comparable angular resolution. The similarity in the structure at all wavelengths indicates that the spectrum doesn't change much across the source. The flux densities of the whole complex out to a radius of 5' (1 kpc) were determined by integrating the emission in circular rings. To ensure a uniform flux determination in all maps the background was assumed to be zero in a ring between 5' and 8' radius from the centre. With this procedure our fluxes can be directly compared to the values at 6 and 11 cm determined by Berkhuijzen et al. (1983). As mentioned before the observations at 2.8 cm did not cover the entire
nuclear source. We estimated the total 2.8-cm flux from the nucleus, using the run of surface brightness along the strip that was measured and assuming spherical symmetry. At 21 cm we derive a higher flux (215 mJy) than HS (160 mJy) because our data includes short spacings. Table 1 summarizes the results. We have also included the flux at 408 MHz (Pooley, 1969). Note that HS incorrectly use only half of the total flux at 408 MHz in their spectral index determination. A spectral index of $-0.75 \pm 0.05$ was calculated from a weighted least squares fit to the fluxes at 49, 21, 11, and 6 cm only, because these were derived in exactly the same way. Figure 4 shows a plot of the spectrum. The fluxes at 408 MHz and 10.7 GHz are consistent with the derived spectral index.

![Figure 3. Maps of the radio continuum emission at three wavelengths.](image)

![Figure 4. The spectrum of the radio continuum emission from the nucleus of M31 within 1 kpc radius. The full drawn line is a weighted least squares fit to the 4 least determined points at 0.41, 1.145, 3.71, and 8.95 GHz.](image)

### 4. The origin of the radio continuum emission

In general, the nuclear continuum emission from spirals can be explained in terms of star bursts and/or accretion on a compact nucleus (Hummel et al., 1984). Neither of these sources seems to be present in M31. Since none of the unresolved components in the 21-cm map appears to be an HII region, the radio data confirm the lack of star formation. Thus no type II supernovae (SN) are to be expected. However, if SN of type I produce similar amounts of relativistic electrons, they will also be of significance for the nonthermal radio emission. Of course, some thermal and perhaps nonthermal emission is expected to originate in the ionized gas region.

#### Table 1. Fluxdensities of the nucleus of M31 within 1 kpc

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>flux (mJy)</th>
<th>reference</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.408</td>
<td>520</td>
<td>Pooley (1969)</td>
<td>scaled by 85</td>
</tr>
<tr>
<td>0.610</td>
<td>395</td>
<td>this paper</td>
<td></td>
</tr>
<tr>
<td>1.412</td>
<td>215</td>
<td>this paper</td>
<td></td>
</tr>
<tr>
<td>2.000</td>
<td>130</td>
<td>Berkhuizen et al. (1983)</td>
<td></td>
</tr>
<tr>
<td>3.350</td>
<td>81</td>
<td>Berkhuizen et al. (1983)</td>
<td></td>
</tr>
<tr>
<td>6.700</td>
<td>31</td>
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</tr>
<tr>
<td>10.700</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
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* On scale of Haars et al. (1977)

a) Energy requirements for the global nonthermal component.

We have calculated the minimum energy $E_{\text{min}}$ (Pacholczyk, 1970) and the corresponding minimum magnetic field strength (Table 2) assuming that all emission is nonthermal. Following Longair (1981) we can estimate the SN rate required to supply the minimum energy. If $T_{\text{SN}}$ is the average time between SN and we assume that each SN produces a SNR $T_{\text{SN}}$, the confinement time of relativistic electrons, and $E_0$ the average energy released in cosmic rays and magnetic field per SN then $T_{\text{SN}}(E_{\text{SN}}/E_0) < T_{\text{SN}}$ for a steady state situation. Typical galactic values for $T_{\text{SN}}$ and $E_0$ are 1 E7 yrs and 5 E50 ergs (e.g. Berkhuizen, 1984). That leads to $T_{\text{SN}} = 4.4$ yrs. If we assume a SN rate of 0.01 per yr ($T_{\text{SN}} = 100$ yrs) for M31 as a whole, half of which are of type I, and we take into account that about 10% from all the light originates from the region with the radio emission (De Vaucouleurs, 1958) then we expect $T_{\text{SN}} = 2$ E3 yrs for the nuclear region. The difference between the computed $T_{\text{SN}}$ and the expected $T_{\text{SN}}$ is not disturbing since the confinement time $T_{\text{SN}}$ may well be lower in the nucleus compared to the disk. In addition $E_0$ is not known very accurately. In any case there seems to be sufficient SN to account for the nonthermal emission.

b) Radio emission associated with the ionized gas.

From the H-beta luminosity one can calculate the expected thermal radio continuum emission, assuming thermal equilibrium between electrons and protons as in an HII region (e.g. Osterbrock, 1974). For Te=10^4 K and the recombination value for H-beta/H-alpha, the observed H-alpha luminosity (JFC, Rubin and Ford, 1971) corresponds to a thermal radio flux at 10.7 GHz of 9 mJy (14 mJy if Te=254 K). Note that this is a lower limit because the H-alpha emission suffers from extinction and because a possible diffuse component in the emission line gas would have escaped detection (JFC). The measured flux at 10.7 GHz within the volume

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where the emission line flux has been determined is only 20 mJy. So it seems that essentially all of the 10.7 GHz flux from the inner region could be thermal. This would mean that the nonthermal radio spectrum would steepen between 6 and 2.8 cm. However, there are good indications that the emission lines are not photoionized as in an HII region, but shock ionized (JFC). In that case the scaling of Hbeta flux to free-free radio emission may be incorrect due to nonequilibrium of ions with electrons and produce an overestimate of the thermal contribution. If the gas is shock ionized the radio emission associated with the optical filaments could be mainly nonthermal, resulting from compression of the magnetic field in the shocked region. Since ample relativistic electrons are probably already present due to SN (see above) no additional acceleration would be required. In principle all radio emission could originate this way. The smooth extended component would be due to the diffusion of the relativistic electrons.

5. Discussion

In recent years it has become clear that the activity in the nuclei of active galaxies may well have low level counterparts in the nuclei of normal galaxies. Indeed, the basic characteristics of the presence of ionized gas with high forbidden line strengths, indicating either photoionization or a power law UV source or shock ionization (Keel, 1983a, b). Sometimes the emission lines are broad with widths up to 1000 or 2000 km/s, e.g. in M31, (Rose and Cecil, 1983) and M3 (Peimbert and Torres-Peimbert, 1981). How does M31 fit in this picture? We have listed the properties of the nuclear region of M31 in Table 2. Although M31 clearly does not have a very greater than about 50 km/s are not required; 2. The ratio of radio to emission line luminosity is very low. In the case of M31 the emission line luminosity is of the same order of magnitude as in M3 but the corresponding radio luminosity is two orders of magnitude higher (Ford et al., 1985). However, these two possible objections may just indicate a different level of activity.

Acknowledgements

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References

Baade, W., 1964, Astrophys. J. 139 1027
Baade, W., 1968, Astron. J. 68 435
Keel, W.C., 1985a, Astrophys. J. 268, 632
Keel, W.C., 1982b, Astrophys. J. 259, 466
Kruit, P.C. van der, 1972, Astrophys. Lett. 11, 173
Sofue, Y., Honda, T., 1984, Nature, 310, 568

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