A Westerbork Survey of Rich Clusters of Galaxies

V. Multi-frequency Observations of the Radio Tail Galaxy NGC 6034 in the Hercules Cluster

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Received May 13, 1977

Summary. Maps of the radio-brightness distribution at 5, 1.4 and 0.6 GHz of the wide-angle head tail radio source 1601 + 17W1 associated with the elliptical galaxy N 6034 in the Hercules cluster are presented. At 5 and 1.4 GHz the Westerbork observations also provided polarization data. The spectral index distributions $\alpha_{5,4}$ along the trails are given. The remarkable asymmetric source structure is discussed and interpreted as the result of an ejection not normal to the velocity of the galaxy. A simple ram pressure model then suffices to describe the observed differences in size, flux density and spectral index distribution of the two trails of the radio source as due to different expansion rates of the blobs in the two trails. We derive a lower limit for the product of the density and the temperature of the intracluster medium $n_e T_e \geq 5 \times 10^{-5}$ ($10^7$ cm$^{-3}$ K) in this part of the Hercules cluster.

Key words: head-tail radio sources — clusters of galaxies — intra cluster medium

I. Introduction

The radio source 1601 + 17W1 was detected and identified with NGC 6034 in the previous survey at 1415 MHz of the Hercules Cluster (Jaffe and Perola, 1975). Because of its distance from the field centre of that survey its flux density was strongly attenuated and only an unresolved peak was detected. Reobservation of the Hercules supercluster at 610 MHz has shown that the source is extended and has a peculiar head-tail structure. It has therefore been observed at 4995 MHz and again at 1415 MHz. The results of the observations at the three frequencies are presented in this paper, along with a discussion on the origin of the peculiar structure. A value $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ is used throughout.

II. Observations and Data Reduction

The operation of the W.S.R.T. is described in Högbom and Brouw (1972). The detailed observation specifications are listed in Table 1. At 610 MHz a full synthesis observation was carried out, which after 4 $\times$ 12 h observing time provided a baseline coverage between 54 and 1476 m in steps of 18 m. Both at 1415 and 4995 MHz one half day observation was made using baselines varying from 72 to 1440 m in steps of 72 m. The observations were reduced as described in previous papers of this series (Jaffe and Perola, 1975; Jaffe and Perola, 1976; Jaffe et al., 1976) using standard WSRT reduction programmes (van Someren Grève, 1974). Fourier transforms of the observations resulted in maps of the brightness distribution of the observed field. Those maps were cleaned from remaining side lobes by means of subtractions of $\delta$ functions using the theoretical synthesized antenna pattern. As a next step subtracted components were restored in the map using only the central positive part of the antenna pattern. The effective r.m.s. (1$\sigma$) noise values in those final maps are given in Table 1. For all the observations the position of the field centre was near 1601 + 17W1, so that the attenuation of the sky flux density due to the primary beam is less than 10%. The

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Date</th>
<th>Field centre</th>
<th>Resolution</th>
<th>r.m.s. noise (Jy/beam area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>610</td>
<td>Aug.-Nov. 1973</td>
<td>RA (1950) = 16°02' 26''</td>
<td>DEC (1950) = 17° 5'24''</td>
<td>FWHM = 55'' x 189''</td>
</tr>
<tr>
<td>1415</td>
<td>Febr. 1976</td>
<td>16°01' 00''</td>
<td>17°12' 0.0''</td>
<td>24'' x 83''</td>
</tr>
<tr>
<td>4995</td>
<td>Jan. 1976</td>
<td>16°01'16.3''</td>
<td>17°20'12''</td>
<td>7'' x 23.5''</td>
</tr>
</tbody>
</table>

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contour maps in this paper are reproduced from the final maps and are not corrected for this primary beam attenuation, while the flux densities quoted in the text are corrected.

Each telescope of the Westerbork array had two crossed dipoles, while each interferometer consisted of two telescopes with dipole pairs positioned at an angle of 45° with respect to each other. This allowed us to measure the $Q$ and $U$ Stokes parameters, and to obtain a map of the linearly polarized intensity at the three frequencies (Weiler, 1973). The noise in these maps is higher by a factor $\sqrt{2}$ than in the total intensity maps.

### III. The Results

#### i) The 1415 MHz Map

The 1415 MHz observations reveal the general structure of the radio source (Figs. 1 and 2). It consists of three main components, an unresolved one (which we shall call the "head"), which contains 68% of the total flux, and two extended components elongated NW and SW, at an angle of about 90° to each other. These two components have a maximum extent, measured from the position of the head component from which they appear to emerge, of 5′7 (NW) and 4′1 (SW); they are also slightly resolved in the NS direction, where they have a maximum angular extent of 66″ (NW) and 142″ (SW). The flux of the three components at all three frequencies is given in Table 2.

Figure 3 shows the amplitude and direction of the electric vector of the polarized radiation. The polarization percentage of the unresolved component is about 1%. This value however is rather unreliable, because it is close to the percentage that is caused by instrumental imperfections. The SW component has a polarization of 12% (4σ), and the NW component of 15%, but only at a 2σ level.

#### ii) The 610 MHz Map

This map is reproduced in Figure 4. Because of the larger beam size at this frequency, the two extended components are partially blended. The angular extent of the NW component is 8.5, significantly longer than at 1415 MHz. Due to severe interference, the polarized flux could not be determined at this frequency.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Flux density compact component (mJy)</th>
<th>Flux density northern trail (mJy)</th>
<th>Flux density southern trail (mJy)</th>
<th>Total flux (mJy)</th>
<th>Total power (W Hz$^{-1}$ sterad$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>610</td>
<td>748 (10)</td>
<td>173</td>
<td>269</td>
<td>1190 (15)</td>
<td>1.4 $10^{23}$</td>
</tr>
<tr>
<td>1415</td>
<td>484 (8)</td>
<td>79</td>
<td>150</td>
<td>713 (12)</td>
<td>8.2 $10^{22}$</td>
</tr>
<tr>
<td>4995</td>
<td>299 (3)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>3.5 $10^{12}$</td>
</tr>
</tbody>
</table>
iii) The 4.995 MHz Map

This map is given in Figure 5. The SW and NW components are below the noise, but the “head” component is now partially resolved. The bulk of radiation is still coming from an unresolved core (RA < 2°, DEC < 6°) containing about 80% of the flux. The remaining 20% comes from a feature which extends 60" to the North (P.A. = 7°) and 42" to the South (P.A. = 196°), before trailing into the noise. Confusion due to the core does not allow us to measure the E–W width of this component, but we note that it certainly extends about 11" to the East of the peak, and that it deviates by about 10° from a straight line through the core.

We find a polarized flux of 5 mJy at the position of the core, which corresponds to 3% polarization, at a 4σ level. The position of the electric vector is in the N–S direction.

iv) Spectral Index Distribution

The values of the spectral indexes $\alpha^{1.4}_{0.4}$ and $\alpha^{5}_{1.4}$ ($\alpha^{5}_{1.4} = -\ln S_{1.4}/\ln S_{5}$) were determined in the following way. First the observations at the highest frequency were convolved to the lower frequency by means of new Fourier transforms. In order to get a similar synthesized beamsize at the two frequencies, only spacings which at both frequen-
Fig. 6. The spectral index distribution $\alpha$ along the northern (Fig. 6a) and southern (Fig. 6b) trail of N6034, see text.

cies have the same length in units of $\lambda$ were used. The resulting maps were "cleaned" and "restored" as described above. For the head of the source we obtained $\alpha_{1.4}^h = 0.42 \pm 0.02$ and $\alpha_{0.6}^h = 0.49 \pm 0.04$. In Figure 6a and b the distribution of $\alpha_{1.4}^n$ along the NW and SW components are shown. The errors quoted arise from noise errors and uncertainties in the primary beam attenuation. One point ($\alpha = 0.45$) of the SW component was corrected since the intensities in the map were shifted due to remaining side lobes of the head. It is remarkable that while in the SW component the spectral index rises slowly from 0.5 to $\sim 1.0$, in the NW component it is throughout $\sim 1.0$. The average values of the spectral index for the SW and NW components are 0.60 and 1.0 respectively.

v) The Optical Counterpart

Jaffe and Perola (1975) identified the radio source 1601 +17W1 with the elliptical galaxy NGC 6034. They measured a position of the estimated centre of the optical image of the galaxy: RA = 16°01'16"2, DEC = 17°20'12". In Figure 7 the field around NGC 6034 is reproduced from a red Palomar Sky Survey glass copy. The diameter of the bright part of the optical image of the galaxy is $\sim 30''$. This introduced an error in the estimated position of the centre of the galaxy of the order of 3'. The difference between the optical position and that of the peak in the head component at 4995 MHz is $-3''$ in RA and $+3''$ in DEC, indicating a positional coincidence between the radio peak and the galactic nucleus.

The galaxy NGC 6034 is an outlying member of the Hercules cluster (A 2151), which, together with A 2147 and A 2152, form a supercluster with an angular extent on the sky of $\sim 4^\circ$. From redshifts published in the literature we have calculated a mean radial velocity of 10880 km s$^{-1}$ for A 2151 with a three dimensional velocity dispersion of 1087 km s$^{-1}$ (Burbidge and Burbidge, 1959). The radial velocity of NGC 6034 is 10200 km s$^{-1}$ (Strittmatter et al., 1974), that is 680 km s$^{-1}$ below the cluster average. The apparent photographic magnitude of this galaxy is 15.2 (Zwicky and Herzog, 1963), which, at the distance of 110 Mpc, corresponds to an absolute $M_p = -20.1$.

IV. Discussion

i) Wide Angle Tails

This radio source can be classified as a wide angle tail (WAT). Not many examples of such sources are known (e.g. 3C465). Recently a certain number have been found in radio studies of clusters (Vallée and Wilson, 1976; Owen and Rudnick, 1976). To our knowledge so far no WAT sources have been found outside clusters of galaxies. Their morphology is considered intermediate between the normal doubles and the tail sources (T) like 3C129, and is attributed to a process of interaction with the intracluster gas through which the parent galaxy is moving at high speed ($\sim 1000$ km s$^{-1}$), similar to that which is thought to be responsible for the T sources [Jaffe and Perola (1973), hereafter referred to as JP; Owen and Rudnick (1976)]. Unfortunately a systematic study of the properties of the WAT sources is not yet available, nor has a detailed model been specifically developed for them. In this discussion we shall limit ourselves to the properties which make this object rather remarkable: the difference in length, brightness and spectral index distribution between the North and South components, and the structure of the "head" at 5 GHz. First however we comment on the effects of the intergalactic medium.
Fig. 7. Composite picture of 1.4 GHz (Fig. 2) and 5 GHz (Fig. 5) radio emission superimposed on a red Palomar Sky Survey copy of the optical field. The accuracy of the superposition is $\sim 3^\prime$. 
ii) Intergalactic Medium

In the case of the \( T \) sources, JP assume that far from the head, where the width of the tail stays practically constant, the internal pressure is balanced by the thermal pressure of the surrounding medium. If we apply this concept to the NW-component (\( H_{\text{eq}} \approx 1.6 \mu G \), for an equal contribution of pressure from relativistic protons and electrons, in the prominent roundish blob at R.A. \( \approx 16^\circ 01^\prime 00^\prime \)) we find \( n_{\text{T}} \geq 5 \times 10^{-5} \), that is the surrounding plasma needs to have a density at least equal to \( 5 \times 10^{-5} \text{ cm}^{-3} \) if \( T \approx 10^7 \text{ K} \). Since NGC 6034 is an outlying member of A2151, we note the order-of-magnitude agreement between these values and those deduced for the outer part of rich clusters on the basis of free-free interpretation of their X-ray emission (e.g. Lea et al., 1973; Cavaliere and Fusco-Ferrain, 1976). In the case of the Hercules super-cluster, the faint X-ray emission detected so far comes from A2147 (Cooke et al., 1977), and a more sensitive X-ray observation is therefore needed before a quantitative comparison between the radio and X-ray properties can be made.

iii) The Asymmetry of the Source

The SW-component is brighter than the other, and although the resolution in \( \delta \) is rather unfavourable for us to observe the actual difference in surface brightness, we estimate that the maximum internal pressure is about 2–3 times larger than in the NW-component. This could be due to a difference in the thermal pressure around the two components or to an excess of ram pressure on the SW-component. The latter explanation can also account for the difference in length, flux and spectral index. We shall prove this in the context of the “discrete blob” model developed by JP for 3C129 and NGC 1265, but only in a partially quantitative way, both because the observed structure is not as clean and regular as in those sources, and because the model itself is probably a very simplified description of the reality.

Let us assume that the two extensions in the 5 GHz structure of the front indicate the direction along which the pairs of blobs are ejected on opposite side. From an inspection of Figure 7, one can see that the difference in length of the two 1.4 GHz components cannot be attributed to projection effects, if the two branches are a symmetrical continuation of those two extensions. Assume now that the members of each pair are intrinsically equal, and that the ejection velocity \( v_e \) makes an angle \( \beta \) with the velocity of the galaxy \( v_g \) which differs significantly from 90°. Since the velocity of each blob relative to the medium goes as \( v = v_0 \exp(-2t/T) \), where the characteristic expansion time \( T \) should be the same for two identical blobs (that is independent of \( v_0 \), the ratio \( v/v_g \) of the velocities of two blobs ejected at the same moment will depend only on \( \beta \) and \( v_0/v_g \), and be constant so long as the ram pressure overcomes the thermal pressure for both plasmoids. Correspondingly the internal pressures \( \approx \) ram pressures will be in the ratio \( (v_0/v_g)^2 \), the blob radii in the ratio \( (v_0/v_g)^{1/2} \) and the fluxes (due only to the difference in the adiabatic expansion losses) in the ratio \( (v_0/v_g)^{-2z-1} \). From the present observations it is not possible to identify a pair of blobs in the two components. However, as a numerical exercise, let us take a ratio \( v_0/v_g = 1.73 \) (corresponding to \( \beta = 60^\circ \) and \( v_0/v_g = 1 \)). This gives a ratio of 3 in the internal pressure and a ratio of 3.7 in the fluxes (with \( z = 0.7 \)), which compares reasonably well with the ratio observed between the two “peak” fluxes in the two components. There is no contradiction with the assumption of a thermal pressure equilibrium for the main portion of the NW-component, if the velocity of the northern blobs as observed now is comparable to the external sound speed. Moreover, the northern branch is longer, as expected from this model, because the stopping distance of the blobs, \( D = v_0/2T \) is smaller by a factor 1.7.

A difference in the spectral index distribution is also expected. The steepening of the spectral index \( \alpha \) in the S-component can be attributed to radiation losses (synchrotron and inverse Compton). The expansion would affect very strongly the value of the frequency \( v_c \) (see JP for its definition) around which the steepening is observed. From Equation (8) in JP, \( v_c(2r_1/r_1)^{-4} \), so to pursue our calculation, when 1415 (MHz)/\( v_c \) = 0.2 in the SW-component (corresponding to an increase of \( \alpha \) from 0.5 to 0.7), it should be 0.6 in the NW-component, and \( \alpha \) about 0.9–1.0. The spectral index in the NW-components is in fact about 1.0, and stays practically constant along its length. This independently confirms our hypothesis that in the NW-component the expansion is now practically halted. In these conditions, the decrease of \( v_c \) with time depends only on the rate of the radiative losses. By requiring that \( v_c \) does not significantly decrease along the NW-component, the radiative lifetime can be deduced and it turns out to be \( 5 \times 10^7 \) year. Since the maximum distance from the galaxy along the N-component is about 150 kpc, the radiative lifetime requires a galaxy speed of at least 3000 km s\(^{-1}\). Such a large value is typically derived, using the same argument, in tile radio sources, but there is no evidence, on statistical grounds, from the measurements of the galaxy redshift, that such speeds are generally attained (in our case the radial velocity of the galaxy is only 680 km s\(^{-1}\) below the cluster average). This fact suggests (cf. Pacholczyk and Scott, 1976) that particles continue to be accelerated well after the ejection, and that this process succeeds to compensate partially for the losses, and insures the very long extensions that are found to be detectable in several tails.

We conclude that the gross properties of the extended components of this source can be understood on the basis of a model where the radio emitting material is expelled from the galaxy in opposite sides and at an angle significantly different from 90° relative to the galaxy.
speed. The latter point is important, because the ejection angle is expected to vary at random from source to source in models where the T and WAT radio sources are assumed genetically similar to the normal doubles, and the bifurcation process is thought to take place in the nucleus of the galaxy, presumably unaffected by the external flow. Note in this respect that for the two “symmetric” double tails 3C129 and NGC 1265 an ejection angle of about 90° had to be postulated (JP), while there are no other objects of this class (T and WAT) that have been studied so far in sufficient detail.

iv) The “Head” Component

Finally, we comment on the remarkable structure of the head as revealed at 5 GHz. Most of the flux in the head is contained in an unresolved component. Because its spectral index ($\alpha = 0.5$) is not that of typical nuclear sources, it is not clear whether it comes from a very compact region or from a volume with size of 1 kpc or so.

The head flux is however a large fraction (about 65%) of the total flux of the source and this indicates that the galaxy is at present in a particularly active phase. It is remarkable that the two extensions at 5 GHz follow almost a straight line over about 55 kpc, though they contain only a tiny fraction of the flux. By comparison, the front branches of NGC 1265 (Miley et al., 1975; Riley and Pooley, 1975) contain bright condensations and show a gentle bending which is already evident on a scale of less than 10 kpc (without taking into account the unknown projection effect, however). This suggests that either the front of NGC 6034 is shielded from the action of the flow over a scale larger than the main body of the galaxy, or that the two extensions have a higher rigidity than in NGC 1265. High momentum per unit mass, but low content of relativistic plasma, has been postulated for the relativistic beams, introduced for modelling of sources like Cyg A (Blandford and Rees, 1975). In fact we do not know how the energy is transported outside the nucleus and how the discrete condensations observed in the tails are generated. The comparison suggests that the presence of the bright condensations, as observed in NGC 1265 to trace the $U$ form of the head, correlate with a relatively low rigidity and vice versa. In a beam model this can be related to the process where the highly directional kinetic energy is randomized into relativistic particles and magnetic field energy.

Another peculiarity of this source is the sharp bend between the northern extension of the head and the N-component. Such a bend is not expected if identical “blobs” with the same velocity are ejected in succession, but it can be explained if the strength of the current activity is larger than the one which led to the extended branches.

These comments are very qualitative, but their aim is to draw attention to some aspects of the T and WAT source phenomenon, which in their complexity seems to show some hints for a better understanding of radio source problems.

Acknowledgements. The authors thank Dr. W. J. Jaffe for his collaboration in the Westerbork cluster survey which led to these observations, the Westerbork Telescope Group and the Reduction Group for their work on the observations and the photographic department of the Sterrewacht Leiden for their work on the figures. E.A.V. acknowledge financial support from the Netherlands Organization for Pure Research (Z.W.O.). The Westerbork Radio Observatory and the Reduction Group are administered by the Netherlands Foundation for Radio Astronomy (S.R.Z.M.) with the financial support of Z.W.O.

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