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High resolution observations of the quasar 3C138

B. J. Geldzahler[1,2,*], C. Fanti[3,4], R. Fanti[3,4], R. T. Schilizzi[5], K. W. Weiler[2,6], and D. B. Shaffer[1,7]

[1] National Radio Astronomy Observatory, Green Bank, WV 24944, USA
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany
[3] Leiden Sterrewacht, Postbus 9513, NL-2300 RA Leiden, The Netherlands
[4] Istituto di Radioastronomia, c/o Istituto di Física "A Righi", Via Irnerio 46, I-40126 Bologna, Italy
[5] Netherlands Foundation for Radio Astronomy, Radiosterrenwacht Dwingloo, Oude Hoogeveensedijk 4, Dwingeloo, The Netherlands
[6] National Science Foundation, Washington, DC 20550, USA
[7] Phoenix Corporation, McLean, VA 22102, USA

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Summary. The compact radio source 3C 138 has been mapped for the first time using very long baseline interferometers in Europe and the US. At 1666 MHz, the entire source is approximately 0$''$.45 (3 kpc, $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) in length with one, widely separated component departing substantially from the overall source linearity. The structure is suggestive of the now common core/one-sided-jet morphology observed in many extragalactic compact radio sources, but it is not clear where the core is located in 3C 138. The structure at 1666 MHz is consistent with that as found 10 yr earlier at 2631 MHz, but the uncertainties in component positions are such that superluminal motions up to $v_{\mathrm{app}}/c \approx 10$ cannot be excluded. The energies in relativistic particles and magnetic field and the magnetic field strength are similar to those found for 3C 147. Under equipartition assumptions, the radiative lifetimes of the relativistic electrons are at most 1000 yr in each source component. Since there is no large scale radio structure ($\gtrsim 10$ kpc) at 1666 MHz in 3C 138, we suggest that the observed jet is inefficient in transferring the energy it carries to large distance and dissipates all of it in the first few kpc and dies shortly thereafter.

Key words: radio sources – quasars

I. Introduction

The radio souce 3C 138 (=4C 16.12=PKS 0518+16=OG 130.2) is identified with a quasar of redshift $z=0.76$ (Burbidge and Kinman, 1966) and visual magnitude $m_v=18.84$ (Sandage et al., 1965). It is one of the few sources in the 3CR catalog which shows a well-defined turn-over in the spectrum at low-frequency ($\nu_{\max} \approx 100$ MHz). It is generally assumed (e.g. Kellermann et al., 1969) that the turn-over is due to synchroton self-absorption.

Early investigations of the structure of the radio source, based on interplanetary scintillation studies at frequencies of 178 MHz (Little et al., 1968) and 81.5 MHz (Readhead and Hewish, 1974), or on interferometric observations at a few spacings and position angles (Anderson and Donaldson, 1967, 410 MHz; Broten et al., 1969; Clarke et al., 1969 at 408 and 448 MHz; Clark and Hogg, 1966 at 2600 MHz; Clark et al., 1968, at 1667 MHz; Kellermann et al., 1971 at 1666 MHz) indicate angular sizes $\sim 0''.4$. The most detailed study of the source presented so far was by Donaldson et al. (1971). They used an interferometer with a baseline of 127 km operating at 2631 MHz ($\sim 1.1\,10^6\,\lambda$) and tracked the source for 12 h. On the basis of these observations they proposed a model consisting of three components: Two point sources ($\theta < 40$ mas) separated by 380 milliarcsec along position angle $-110°$, and an extended component (40×300 mas) centered on the eastern point source and also elongated along position angle $-110°$. The eastern point source had a flux density about three times larger than the western one.

We present below the results of very long baseline interferometer observations of 3C 138 at 1667 MHz which reveal for the first time the detailed structure of this object.

II. Observations and data analysis

The data were obtained in two observing sessions: (1) 26–28 October 1977, and (2) 6–8 January 1978 using the 2 MHz bandwidth Mk II VLBI system (Clark, 1973). Table 1 presents the details of the individual antenna systems involved in the study and

Table 1. Antenna parameters

Station	Diameter (m)	Session	System Noise (K)	Sensitivity (Jy/K)	Frequency Standard
Dwingeloo	25	2	40	10	Rb
HRAS*	25	1	120	10	Rb
Hat Creek	25	1	130	10	Rb
Haystack	37	1	200	16	Maser
Jodrell	76	2	175	1	Rb
MPIfR*	100	2	75	0.8	Maser
NRAO*	43	1	60	3.2	Maser
Onsala	25	2	30	10	Maser
OVRO*	40	1	75	5	Maser
VRO*	37	1	100	5.2	5 MHz crystal oscillator

* HRAS = Harvard Radio Astronomy Station
MPIfR = Max Planck Institut fur Radioastronomie
NRAO = National Radio Astronomy Observatory, Green Bank, WV
OVRO = Owens Valley Radio Observatory
VRO = Vermillion River Observatory

Send offprint requests to: B. J. Geldzahler (Washington address below)

[*] Present address: E. O. Hulburt Center for Space Research, Code 4134 G, Research Laboratory, Washington, DC 20375, USA

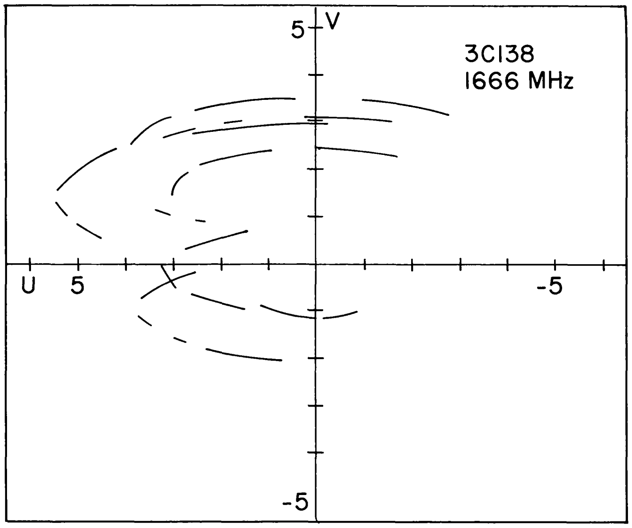

Fig. 1. (u, v)-plane coverage used for mapping 3C138 at 1666 MHz

includes the telescope diameter, the session in which the telescopes were used, approximate system temperature, peak sensitivity, and the type of frequency standard employed. Circularly polarized feeds were used at all stations except at the Owens Valley Radio Observatory, where a linear feed was used. The observing frequency was 1671 MHz during session (1) and 1666 MHz during session (2). System noise temperatures were measured on the hour as well as before the first and after the last observation of the source by injecting a known amount of noise into the receivers.

The data recorded during session (1) and (2) were processed on the NRAO Mk II VLBI correlator (Clark, 1973) and the MPIfR Mk II VLBI correlator, respectively.

The (u, v)-plane coverage used for mapping 3C138 is shown in Fig. 1. This is only a part of the (u, v)-plane sampled by the observations since for spatial frequencies greater than about $5\,10^6$ wavelengths, the source is heavily resolved. Only on the European baselines and Haystack-NRAO was the source detected. Furthermore, a correlator malfunction during the processing of the session (2) data allowed the closure phase around only one baseline triplet (Effelsberg, Dwingeloo, Jodrell) to be determined and used in the mapping procedure.

The amplitude data were calibrated according to the method outlined by Cohen et al. (1975). The absolute calibration of each interferometer was obtained by observing BL Lac and OQ 208 [the second source only for session (2)], which were unresolved on all baselines. The measured fringe amplitudes of the calibrators were adjusted to match the measured single dish flux densities obtained at the same epoch. The flux densities for BL Lac and OQ 208 were 3.5 and 1.0 Jy, respectively. The calibration factors obtained from the two sources were consistent to within 8%. Of the great number of baseline intersections possible in the (u, v)-plane coverage of 3C138 only one was, in fact, observed due to scheduling constraints. The calibrated amplitudes were initially discrepant by 11% at that point but were then adjusted to be in agreement.

Figure 2 shows the brightness distribution of 3C138 at 1666 MHz determined using the mapping procedure of Cotton (1979). An independent determination of the structure was also made by applying a model fitting procedure to the amplitudes, with substantially similar results. The dynamic range on the map is of the order of 10 to 1, owing to the uncertainties in the amplitude calibration. It is possible, therefore, that some of the details indicated by the lowest level contours are not real.

II.1. The structure of the source

The overall angular extent of 3C138 is about 0.″45 along position angle 70° in good agreement with all previous estimates of size made in the frequency range 80 MHz to 2.7 GHz, and particularly with the structure model proposed by Donaldson et al. (1971). The map presented here fully accounts for the total flux density of the source measured at the epoch of the observations (8.07 Jy) suggesting that there are no larger components at this frequency which have been fully resolved. The most striking feature in the map of 3C138 is the elongated nonlinear structure which has some similarity to the jet-like structure seen, for instance, in M87 (Wilkinson, 1974), 3C147 (Wilkinson et al., 1977), 3C273, 3C345 (Readhead et al., 1979). The structure is composed of three main brightness peaks embedded in elongated low level emission. The three peaks and the broad component can be described in terms of

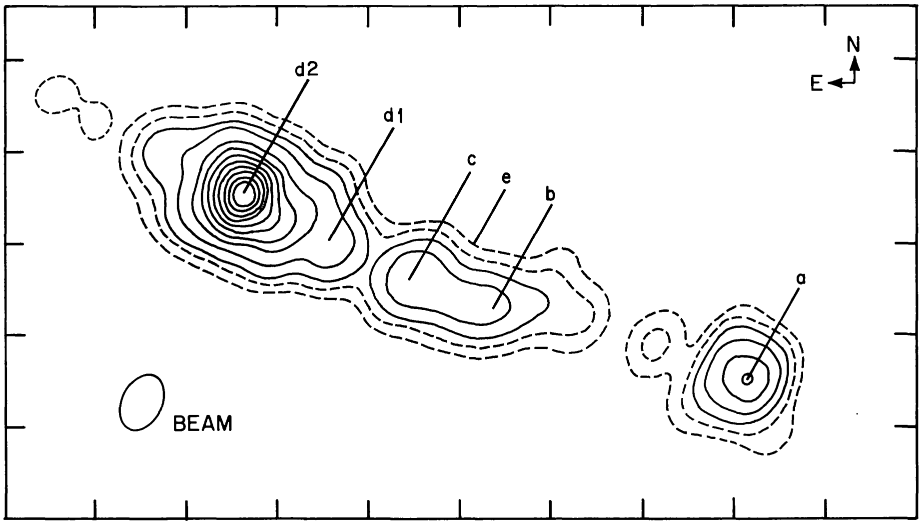

Fig. 2. The brightness distribution of 3C138 at 1666 MHz. The contours represent the 1, 2.5, 5, 10, 20, ..., 90% levels of the peak brightness which is $4\,10^6$ Jy arcsec^{-1} after smoothing with an elliptical Gaussian beam of size 41 × 28 mas along position angle 154°. The axes are graduated every 75 mas

1984A&A...131..232G

Table 2. Component parameters of 3C 138 at 1666 MHz

Comp.	Radial Dist. (mas)	P.A. (deg)	Flux Density (Jy)	Angular Size (FWHM) (mas)	T_b (K)
a	0.0	--	0.76	15x15	1.7×10^9
b	254.5	74.2	0.61	25x39	3.0×10^8
c	326.5	72.1	0.77	35x35	3.0×10^8
d1	370.9	69.7	0.76	35x35	3.0×10^8
d2	399.4	70.2	2.10	26x30	1.3×10^9
e	270.0	70.0	3.00	40x400	1.0×10^8

Table 3. Comparison with the model of Donaldson et al. (1971) at 2631 MHz

1666 MHz			2631 MHz			α(1666,2631)
S (Jy)	Dist. (mas)	Max Size (mas)	S (Jy)	Dist. (mas)	Max Size (mas)	
1.01	--	5	0.9	--	40	-0.24
3.40	391	62	2.5	380	40	-0.64
3.70	275	382	2.6	380	400	-0.73

six elliptical Gaussian components whose parameters are given in Table 2. Column 1 identifies the component, Column 2 gives the radial distance from component a, Column 3 the position angle of the component's location north through east, Column 4 the component flux density, Column 5 the sizes (FWHM) of the minor and major axes, and Column 6 the brightness temperature. The approximate location of each component is shown on the hybrid map in Fig. 2. These "components" qualitatively describe the source structure but do not necessarily correspond to physical plasmons. The structure is suggestive of a core-jet morphology, but it is not clear which component is the core. Comparisons with morphologies of other jets are not conclusive in this respect, since the examples of 3C 273 and 3C 345 might suggest that the core is near component *d*2, while the example of M87 would indicate component *A* is a possible candidate. All the bright components must have angular sizes > 10 milliarcsec in order to be undetected on the longer intra-US baselines.

The core would generally be identified with the component which has the flattest spectrum. A crude estimate of component spectral indices can be made by comparing our 1666 MHz data on the Effelsberg-Dwingeloo baseline with the 2631 MHz data of Donaldson et al. (1971), assuming no time variation of the flux density, as both baselines have the same orientation and length ($\sim 1.1\,M^{\lambda}$) and thus a comparable resolving power. This analysis, fitting only a 3 component model to the 1666 MHz data, to be consistent with the 2631 MHz result, suggests that component "*a*" has the flattest spectrum (see Table 3). Some confirmation is given by the results of a short (1 h) observation at 6 cm obtained with the European network (Onsala–Effelsberg–Westerbork–Jodrell Bank). The limited data indicate that component "*a*" is the most compact and has perhaps the flattest spectrum between 18 and 6 cm, but no definite statement is possible at this time. A final possibility, and the most intriguing one, is that the true core is not represented by either *A* or *d*2, but is self-absorbed at 1.6 GHz. In this case, the structure seen at 1.6 GHz represents a disembodied "naked jet". Only high-frequency, high resolution observations of 3C 138 will be able to determine the location of the core.

III. Discussion

III.1. A relativistic jet?

Several authors (e.g. Scheuer and Readhead, 1979) have suggested that asymmetric, one-sided sources such as 3C 273 and 3C 345 are actually relativistic twin jets oriented close to the line of sight. The jet pointing toward the observer would be brightened because of beaming effects by a factor $D^{2+\alpha}$, D being the Doppler factor (Blandford and Konigl, 1979), while the brightness of the receding jet would be dininished by a similar amount. Also, the fact that these sources do show large changes of their position angle (Readhead et al., 1979) can be simply explained in terms of projection effects which emphasize any deprojected change in direction by a factor $\simeq \operatorname{cosec}\theta$ (θ being the angle between the main jet axis and the line of sight). In order to justify the one-sided jet appearance of 3C 138 in terms of beaming effects, values of $\beta\cos\theta = v/c\cos\theta \gtrsim 0.4$ are required. Unless the source is at a very large angle to the line of sight, the jet does not need to be highly relativistic. The comparison between our map and the structure modeled by Donaldson et al. (1971) does not show any significant structure change, but the uncertainties in the position of the components are such ($\simeq 10$ milliarcsec) that superluminal motions up to $v_{\mathrm{app}}/c \approx 10$ cannot be excluded.

III.2. Physical parameters in the source

Table 4 presents some physical parameters of the source components assuming values of $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 1$. Equipartition magnetic fields and internal energies are computed assuming a ratio of protons to electrons equal to unity (e.g. Pacholczyk, 1970). We have assumed a cylindrical geometry for

Table 4. Physical parameters of the components of 3C 138

Comp.	L(W/Hz)	Projected Linear Size (pc)	u_{min} (erg/cm^3	H_{eq} (Gauss)	U_{min} (erg/cm^3)	νm (MHz) $-0.25 < \nu < -0.75$	τs (Yrs.)	Projected Distance from a (kpc)
a	5×10^{26}	55x55	2×10^{-6}	6×10^{-3}	16×10^{54}	400-450	8×10^2	---
b	4	90x140	5×10^{-7}	3×10^{-3}	4×10^{55}	190-260	2×10^3	1.8
c	5	130x130	4×10^{-7}	2×10^{-3}	8×10^{55}	190-260	4×10^3	2.3
d1	5	130x130	4×10^{-7}	2×10^{-3}	8×10^{55}	190-260	4×10^3	2.6
d2	13	90x100	1×10^{-6}	4×10^{-3}	8×10^{55}	355-385	1×10^3	2.8
e	19	150x1500	2×10^{-7}	2×10^{-3}	4×10^{55}	115-155	4×10^3	1.9

each component. No corrections have been introduced for beaming due to relativistic motion, since from what is known and discussed above, the latter does not need to be large. Energies and magneitc field strengths are rather similar to those found, with similar assumptions, e.g., for 3C 147 (Wilkinson et al., 1977).

III.3. The spectrum of the source

We have estimated the frequencies ν_m at which synchrotron self-absorption should cause a spectral turn-over in the various components on the basis of the measured flux densities and sizes and the equipartition field H_{eq}. These frequencies are given in Table 4, Column 7 for a range of spectral indices of the components ($0.25<\alpha<0.75$). A plausible explanation for the low-frequency turn-over in the spectrum is synchrotron self-absorption although the ν_m computed from the model occurs at a frequency twice as high as the observed frequency. The dominant component at $\nu_m<200$ MHz of the 6 listed in Table 2 is expected to be the broad component *E*. To gain a better agreement we must assume that the size of this component is larger than our estimate by a factor of 2, or that its magnetic field is lower than the equipartition value by about an order of magnitude. Relativistic beaming could also reduce the discrepancy, although it would require a Doppler factor $D \simeq 10$ to remove it completely. A more plausible explanation is that main contributor to the radiation around 100 MHz comes from a larger component not seen in the present observations. Such a component should have a spectral index $\alpha \geqq -1.5$ in order to have not been detected in our 1.6 GHz observations.

The integrated radio spectrum also steepens by $\Delta\alpha \simeq 0.2$ at 3 GHz. With the present paucity of data we cannot decide whether this is due to synchrotron self-absorption in some compact component or if it is a steepening in the transparent part of the spectrum due to energy losses of the relativistic electrons.

III.4. Polarization

3C 138 is known to exhibit a high degree of linear polarization ($\sim 7\%$) at 1666 MHz (cf. Tabara and Inoue, 1980). After correction for Faraday rotation, the intrinsic position angle of the electric field is found to be $\sim 170°$ which implies a magnetic field direction of $\sim 80°$, remarkably close to the position angle of the overall radio structure. The origin of the polarized emission remains unknown. If it were distributed all through the source, 3C 138 would be similar to the inner parts (few kpc) of the other well studied jets such as 3C 31, NGC 315, etc., in which the magnetic field is aligned with the jet. The main differences would then be the radio luminosity, which in 3C 138 is about 4 orders of magnitude larger than in other classical large-scale jets, and the lack of a second region where the magnetic field flips to the perpendicular direction.

The observed depolarization (Tabara and Inoue, 1980), if interpreted as due to internal Faraday rotation, implies an internal thermal plasma density $<10^{-3}\,\mathrm{cm}^{-3}$ (assuming $H_{||} \simeq 10^{-3}$ gauss and a size of the source along the line of sight ~ 100 pc), or $\lesssim 10^3\,M_\odot$ in the radio source. Turbulence could also cause the observed depolarization. However, the result is likely not to change much under this interpretation (cf. Burn, 1966).

III.5. Confinement of the source

Assuming equipartition, the lack of any clear break in the source spectrum (except a small steepening at 3 GHz) strongly suggests that the electrons radiating at the moment are younger than a few times 10^3 yr. This is shorter than the light travel time along jet and suggests the radiating electrons are accelerated in situ. The assumption of equipartition can, however, lead to misleading conclusions. The source might not be in equilibrium, and if the magnetic field strength were to be an order of magnitude less than H_{eq}, the lifetimes of the electrons would be 100 times larger and, thus, reacceleration along the beam would not be required. In this case, the lifetimes are comparable to the light travel time along the entire observed jet length.

A stronger argument for the need for local acceleration is found when considering the problem of the confinement of the source since it is likely that the "jet" is not confined. Its internal generalized sound speed is $(u_{\mathrm{int}}/\varrho_{\mathrm{int}})^{1/2}$ (cf. Longair et al., 1973) and is close to the speed of light ($>c/3$). Static confinement by an external medium requires that the internal pressure $\approx$ external static pressure $\approx n_e k T_e$, i.e. – that $n_{\mathrm{ext}} T_{\mathrm{ext}} \simeq 10^9\,\mathrm{cm}^{-3}$ K. Actually, the low Faraday rotation observed in the source requires external densities $<1\,\mathrm{cm}^{-3}$ for $H_{\mathrm{ext}} \gtrsim 10^{-7}$ G over ~ 1 kpc region. This would require $T_{\mathrm{ext}} > 10^9$ K. While this range of densities and temperatures does not violate the observed X-ray luminosity of the source (Zamorani et al., 1981), another problem arises. Such a hot gas would be difficult to confine, requiring a confining mass of $10^{13}\,M_\odot$ within 1 kpc radius, and would escape at a rate of $\approx 3\,10^2\,M_\odot\,\mathrm{yr}^{-1}$, requiring a corresponding rate of mass replenishment which seems too high.

Ram pressure confinement would be achieved with velocities $\gtrsim 0.1c$, maintaining the condition $n_{\mathrm{ext}} < 1\,\mathrm{cm}^{-3}$. However, a well-known condition for ram-pressure confined plasmons is that they must be denser than the surrounding medium by a factor equal to the ratio of the distance traveled to their size. This again is in contradiction to the observed depolarization rate and the inferred thermal plasma density. It can, therefore, be concluded that confinement is quite unlikely and that particles leave their production site at a speed close to that of light. Unless the source is a very short-lived phenomenon (≈ 300 yr), energy has to be supplied continuously or quasi-containuously at a rate of about:

$$U_{\min}\left(\frac{c/3}{\text{transverse size}}\right) = 10^{46}\,\mathrm{erg\,s}^{-1} \tag{1}$$

roughly 1 order of magnitude larger than the radio luminosity we actually observe. This rate of energy supply is of the same order of magnitude as that of kinetic energy flow of the $10^{-3}\,\mathrm{cm}^{-3}$ thermal plasma at a speed near that of light ($\approx 10^{46}\,\mathrm{erg\,s}^{-1}$ for $\gamma \approx 2$). The above arguments might be somewhat reduced if the jet is largely relativistic. The beaming effect produced by the relativistic bulk motion would lead to a brightness which is a factor $D^{2+\alpha}$ larger than the one observed in the co-moving frame of the source. Correspondingly, we would have overestimated the energy content. However, in order to have a substantial reduction of the problem (e.g., an expansion velocity substantially lower) we would require a bulk Lorentz factor $\gtrsim 10$.

IV. Conclusion

The radio source 3C 138 has a jet-like structure very similar in several respects to other well-studied jets in low-luminosity radio sources, but with a much larger radio luminosity. The presence of significant polarization, if distributed throughout the source, poses limits to the amount of thermal plasma contained in the jet and indicates that the jet must expand in the transverse dimension at near the speed of light. No external confinement is likely to occur. Unless this a very short lived phenomenon or it has a very large Lorentz factor, the source has to be losing energy at a rate of $\sim 10^{46}\,\mathrm{erg\,s^{-1}}$ and then must have energy replenishment at a similar rate. The basic source of energy supply may be the kinetic energy of the plasma if the jet is moderately relativistic ($\gamma \sim 2$). An energy supply of $10^{46}\,\mathrm{erg\,s^{-1}}$ would be large enough to feed any strong extragalactic radio source. There is no evidence for an extended radio component in 3C 138 at 1666 MHz, perhaps because the source is relatively young and has not had sufficient time to create an extended component or, perhaps, because it has a very steep spectrum. Even if the beam in 3C 138 is relativistic, an extended component might be faint or not visible as in the cases of 3C 120 or 3C 273. It is, however, tempting to conclude that the jet we see in 3C 138 is inefficient in transferring the energy it carries to large distances and dissipates all of it, either by bulk kinetic energy losses (e.g., jet expansion or turbulence) or in the first few kpc and then quickly dies. A search for very low frequency emission on VLBI scale sizes is not technically feasible at this time due to the lack of adequately equipped antennas located at suitable interferometer spacings. If such low frequency VLBI observations could be made, the source size should appear larger at the low frequency than at 1666 MHz if very low-frequency emission is responsible for the energy loss in the beam.

Further observations of this source are necessary in order to verify many of the suggestions above. Particularly important would be a mapping of the distribution of the polarized emission.

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Note added in proof: Recent 6 cm MKIII VLBI observations of 3C 138 (N. L. Cohen and B. J. Geldzahler, private communication) show that component "*a*" is resolved on a baseline of 65 million wavelengths strongly suggesting that component "*d2*" is the actual core.