Combined-array images of an archetypal compact steep-spectrum source, 3C147

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SUMMARY
We present an EVN map at 1.67 GHz and combined EVN–MERLIN maps at 1.67 and 5 GHz of the compact steep-spectrum radio source 3C147. The maps reveal three dominant extended regions and a bright core. The structure cannot be readily explained with the standard relativistic beaming model. A sharp bend in the VLBI jet, and the overall distorted structure may be caused by the interaction of the jet with ambient gas, though we cannot rule out a multiengine source each with its own jet. Physical parameters of the knots along the VLBI jet and the age of 3C147 have been estimated.

1 INTRODUCTION
The quasar 3C147 (z = 0.545, nv = 17) is an archetypal compact steep-spectrum (CSS) source. It has been well studied by many investigators with the VLA, MERLIN and VLBI (VLA: Readhead, Napier & Bignell 1980; van Breugel, Miley & Heckman 1984; Pearson, Perley & Readhead 1985. MERLIN: Wilkinson et al. 1984; Akujor, Spencer & Wilkinson 1990. VLBI: Wilkinson et al. 1977; Readhead & Wilkinson 1980; Simon et al. 1983; Simon, Readhead & Wilkinson 1984, 1990; Alef et al. 1988; Zhang et al. 1990a,b). There are three extended features elongated along p.a. ~ 20°, ~ 145° and ~ 230° and, although Fanti et al. (1990) classify 3C147 as a triple source, the radio structure is actually quite complex. Alef et al. (1988) have also reported the detection of superluminal motion in the core of 3C147 with an apparent v/c = 2.6 ± 1.0.

In this paper we present new radio images of 3C147 made from data obtained with the European VLBI Network (EVN) at 1.67 GHz and with a combination of data from the EVN and MERLIN (Thomasson 1986) at 1.67 and 5 GHz. The combined maps have enabled us to clarify the connection between the three main extended features and the bright radio core. The physical parameters of the knots along the VLBI jet and the age of 3C147 have been estimated.

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2 OBSERVATIONS AND DATA REDUCTION
The data were obtained at different epochs of observations. The EVN observations were made at epoch 1982.93 (5 GHz) and epoch 1987.86 (1.67 GHz), while the MERLIN observations were made at 1982.28 (5 GHz) and 1983.14 (1.67 GHz). The telescopes used are listed in Table 1.

It is difficult to map large-scale structure from VLBI observations alone because of the short lack of spatial sampling, while on the other hand the resolution of MERLIN is too low for mapping fine structure on the milliarcsecond (mas) scale. From Table 1, the minimum baseline BONN–WSRT in EVN is ~ 210 km, while the maximum baseline DEFFORD–TABLEY in MERLIN is ~ 132 km, and so the shortcomings can be overcome by combining EVN and MERLIN data; the

<table>
<thead>
<tr>
<th>Table 1. Antennae used.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MERLIN</strong></td>
</tr>
<tr>
<td>1.67 GHz (1982.14)</td>
</tr>
<tr>
<td>5 GHz (1982.28)</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>DEFORD</td>
</tr>
<tr>
<td>TABLEY</td>
</tr>
<tr>
<td>IMوخ</td>
</tr>
<tr>
<td>KNOX Hall</td>
</tr>
<tr>
<td>DARNHALL</td>
</tr>
<tr>
<td>WARDLE</td>
</tr>
<tr>
<td>MCKY</td>
</tr>
<tr>
<td>CSOLA</td>
</tr>
<tr>
<td>BOLOGNA</td>
</tr>
<tr>
<td>WSRT</td>
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<td>EFFELSBERG</td>
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combined data are useful for obtaining structural information on intermediate, i.e. tens of mas, scales.

Linking VLBI and MERLIN data together requires care to be taken as follows.

1. There is a systematic difference (∼ 0.58 km) between the coordinates of VLBI telescopes and those used for MERLIN. The visibilities should be recalculated in the same coordinate system before linking them together. The VLBI coordinate system was used in our calculation.

2. The sensitivities can be very different for the different antennas. For high S/N data, telescope tracking errors and errors in gain calibration are likely to dominate and so we assigned the same weight to data from all antennas.

3. A rotation correction (∼ 0.35, due to precession) was used to bring each separate data set to the same reference epoch (1950.0).

4. The systematic calibration difference between the VLBI data set and MERLIN data set was removed by comparison of the measured flux density of calibration sources.

All the maps were made using the Jodrell Bank OLAf and the NRAO aips packages. The map program of OLAf was used to correct for telescope-based amplitude and phase errors by iterative self-calibration. A difference mapping approach is used in this program as outlined by Cornwell & Wilkinson (1984) and Muxlow et al. (1988).

After correction the final maps were made in aips using the program MX. The surface brightness sensitivity of the 1.67-GHz maps is superior to those at 5 GHz because we had better uv coverage at 1.67 GHz in both MERLIN and VLBI observations.

3 RESULTS AND DISCUSSION

Fig. 1 is the map made from EVN data alone at 1.67 GHz. The restoring beam is 20 × 15 mas2; +90°. The map shows the well-known core–jet structure of 3C147. The jet has a length of ∼ 230 mas in p.a. ∼ 230°. A number of knots, labelled K1, K2, K3 and K4, are visible in the jet. The component C is identified with the core of the source (Alef et al. 1988). The tip of the source in the SW, where the jet turns towards the NW, is edge-brightened. Some parameters, including flux density, distance from the reference point and geometric parameters, of the core and the components were obtained using model-fitting and are listed in Table 2. The flux density in this map is only ∼ 40 per cent of the total flux density from single-dish measurements, thus there is larger scale structure around the features shown in Fig. 1.

Fig. 2(a) shows the 1.67-GHz combined EVN–MERLIN map with the restoring beam of 30 × 30 mas2. The core and the 0.2-arcsec VLBI jet shown on Fig. 1 are now seen to be embedded in extended emission. Three extended features, labelled E1, E2 and E3, lead off to the N, SE and SW, as in the 329-MHz VLBI maps by Simon et al. (1990). Fig. 2(b) shows the combined EVN–MERLIN map at 5 GHz with a restoring beam of 20 × 20 mas2. The extended structures E1 and E2 are only just detected, and the dynamic range of the 5-GHz combined map is too low to reveal more details of these emissions.

The maps taken together now clarify the connection between the three main extended features. Both the 1.67- and 5-GHz combined maps exhibit a direction change of the SW jet at its tip as in the 1.67-GHz VLBI map. At the dynamic range level of our maps, there is no evidence that the jet turns round to join either the extended structure E1 or E2. The SE extended feature E2 does not appear to join directly to the core, but rather joins either to E1 or curves round through ∼ 70° before joining the core.

Using the combined EVN–MERLIN maps, we can obtain the spectral index and its variation along the SW jet; this is shown on grey-scale in Fig. 3. The mean spectral indices α of the core and the knots are listed in Table 2 (S ∝ να). At the knot K4, the mean spectral index is flat and the index hardens considerably towards its SW edge, suggesting that K4 marks a place where interaction with external gas clouds may be taking place resulting in the sharp bend of the jet at

![Figure 1. EVN map of the radio source 3C147 at 1.67 GHz. Restoring beam: 20 × 15 mas2; +90°. Contour levels are (−0.5, 0.5, 1, 2, 4, 8, 16, 32, 64, 99) per cent × 2.01 Jy beam−1.](https://academic.oup.com/mnras/article-abstract/250/3/650/998576)

Table 2. Observed and physical parameters* for 3C147.

<table>
<thead>
<tr>
<th>Comp</th>
<th>d (mas)</th>
<th>S (ν)</th>
<th>Ang. size (mas)</th>
<th>α</th>
<th>Lin. size (pc)</th>
<th>Umin (10^12 erg)</th>
<th>ρ (10^8 g/cm^3)</th>
<th>B_eq (gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>2.09</td>
<td>5x2</td>
<td>43</td>
<td>0.34</td>
<td>43x16</td>
<td>6.0</td>
<td>20.70</td>
</tr>
<tr>
<td>K1</td>
<td>40</td>
<td>0.32</td>
<td>22x12</td>
<td>164</td>
<td>0.92</td>
<td>192x101</td>
<td>26.2</td>
<td>0.63</td>
</tr>
<tr>
<td>K2</td>
<td>84</td>
<td>0.73</td>
<td>34x16</td>
<td>53</td>
<td>0.45</td>
<td>299x136</td>
<td>38.4</td>
<td>0.32</td>
</tr>
<tr>
<td>K3</td>
<td>165</td>
<td>0.55</td>
<td>35x22</td>
<td>64</td>
<td>0.70</td>
<td>309x194</td>
<td>52.8</td>
<td>0.23</td>
</tr>
<tr>
<td>K4</td>
<td>190</td>
<td>0.71</td>
<td>22x12</td>
<td>154</td>
<td>0.50</td>
<td>193x108</td>
<td>51.6</td>
<td>0.62</td>
</tr>
</tbody>
</table>

* H₀ = 100 km s⁻¹ Mpc⁻¹; q₀ = 0.5.

d = distance from the reference point; S = knot flux density; α = spectral index; Umin = minimum total energy; ρ = minimum energy density; B_eq = equipartition magnetic field.

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Figure 2. EVN-MERLIN combined maps of radio source 3C147 at 1.67 and 5 GHz, respectively. (a) The combined 18-cm map. Restoring beam: $30 \times 30$ mas$^2$. Contour levels are $(-0.5, 0.5, 1, 2, 4, 8, 16, 32, 64)$ per cent $\times 2.26$ Jy beam$^{-1}$. (b) The combined 6-cm map. Restoring beam: $20 \times 20$ mas$^2$. Contour levels are $(-0.5, 0.5, 1, 2, 4, 8, 16, 32, 64, 99)$ per cent $\times 1.95$ Jy beam$^{-1}$.

Figure 3. Grey-scale plot of variation of spectral index along the jet superimposed on 5 GHz contours (restoring beam is $20 \times 20$ mas$^2$).

its SW tip. Faraday rotation measurements have provided evidence for the presence of large amounts of gas in or around 3C147 (Kato et al. 1987).

The physical parameters for the jet knots of 3C147 have been estimated by assuming the usual equipartition conditions and using standard formulae (Pacholczyk 1970). No correction has been introduced for beaming due to relativistic motion. The observed and calculated physical parameters for 3C147 are listed in Table 2. The parameters of the jet in 3C147 are similar to that of some other CSS's, e.g. 3C49, 3C138 and 3C287 (Fanti et al. 1989).

If there is equilibrium between the non-thermal pressure inside the knot K4 and the dynamic pressure of the outer ambient medium, so that the pressure and energy density are at minimum values $p_{\text{min}}, \ u_{\text{min}}$, then the velocity $v$ of expansion can be estimated from the relation

$$m_p n_e v^2 \approx p_{\text{min}} \approx 0.5 u_{\text{min}},$$  \hspace{1cm} (1)$$

where $m_p$ is the proton mass and $n_e$ the external gas density ranges from 1 to 10 cm$^{-3}$. Assuming a particle density of $n_e = 1$ cm$^{-3}$ for the hot diffuse component (Fanti et al. 1990) and using the parameters listed in Table 2, we can calculate the pressure: $p_{\text{min}} \approx 3 \times 10^{-7}$ dyne cm$^{-2}$ and derive an upper limit of velocity for the jet head of $v \geq 4 \times 10^8$ cm s$^{-1}$. To travel an angular distance of $230 \text{ mas}$ ($\approx 2.0 \text{ kpc}$), the jet head must have taken some $5 \times 10^5$ yr. Using the length of $\approx 7 \text{ kpc}$ of the northern feature E1, the age is about $2 \times 10^6$ yr. This conforms with typical dynamical time-scales for CSS's (Fanti et al. 1990). Any projection effects will of course increase the age estimate.

The structure of 3C147 on the subarcsec scale shown by the 1.67- and 5-GHz combined maps is very complex as is also indicated by the 5-GHz VLBI map (Preuss et al. 1982) of the nucleus of 3C147. What is responsible for this complicated structure? Even though superluminal motion in the core of 3C147 has been suggested, the asymmetric structures on both subarcsec and mas scales observed in 3C147 cannot
easily be explained in terms of simple symmetric beaming models. In these the apparent asymmetric appearance is caused by the differential Doppler beaming of the approaching and receding components. The principal effect of velocity $\beta = v/c$ on the geometry of radio structure arises from the light traveltime, $(1 - v/c)^{-1}$, which causes a stretch of an approaching jet and compression of a receding jet. A stretch factor $f$ as the ratio of the angular distance from the source to features in the approaching and receding beams is

$$f = \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta}.$$  

(2)

The jet-to-counter-jet brightness ratio $R = f^\eta$, where $\eta = (3 - \alpha)$ for individual components, or $(2 - \alpha)$ for a continuous jet (Scheuer & Readhead 1979; Blandford & Königl 1979; Gower et al. 1982; Unwin et al. 1989). Both $f$ and $R$ are $\geq 1$ and provide strong constraints on the jet kinematics. The extended features of 3C147 do not fit the simple two-sided jet picture. If E1 or E2 was the receding beam, then no solution for the equation (2) could be found from the observed ratio in 3C147, since the receding beams appear longer than the approaching beam. On the other hand, if E1 or E2 was the approaching beam, then the brightness ratio $R$ could not be satisfied. It is possible that some degree of projection and hence Doppler-boosting of the compact components may be due to the superluminal motion in the core, but orientation effects alone cannot account for the peculiar shape of 3C147.

4 CONCLUSIONS

3C147 is one of the most apparently distorted CSS sources. Our combined maps reveal the extended structures on subarcsec scales and their connections to the core. Although superluminal motion in the core has been suggested, the relativistic effects on a basically symmetric source cannot easily explain the asymmetric structures on both subarcsec and mas scales.

The structure of 3C147 is difficult to explain without invoking the existence of an inhomogeneous, dense and possibly clumpy medium with which the jet is violently interacting. This may be responsible for the partial disruption of the beam (or jet) to the south close to the nucleus, resulting in three extended emission regions from an initially two-sided structure. This may also be responsible for the fragmentation of the jet, for the spectral hardening in the knots and the abrupt deflection of the jet near the terminal knot.

High-resolution VLBI observations of 3C147 reveal that the nucleus has an equally complex non-linear structure. There are at least three extensions with respect to the brightest component located in the middle. It is still unclear where the actual core is located (Preuss et al. 1984). From the complex structure of 3C147 on both subarcsec and mas scales, we cannot rule out another possibility, namely that the complexity of 3C147 is intrinsic, and there could be more than one engine in the centre, each with its own jet.

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