THE CENTER OF ACTIVITY IN THE COMPACT STEEP-SPECTRUM SUPERLUMINAL SOURCE 3C 138

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ABSTRACT

We present the results from the first quasi-simultaneous multifrequency (2.3, 5.0, 8.4, and 15 GHz) very long baseline interferometry (VLBI) observations of the compact steep-spectrum (CSS) superluminal source 3C 138. For the first time, the spectral distribution of the components within its central 10 milliarcsecond (mas) region was obtained. This enables us to identify the component at the western end as the location of the nuclear activity, assuming that the central engine is associated with one of the detected components. The possibility that none of these visible components is the true core is also discussed. The new measurements further clarify the superluminal motions of its inner jet components. The multifrequency data reveal a convex spectrum in one jet component, implying the existence of free-free absorption by the ambient dense plasma.

Subject headings: galaxies: active — galaxies: jets — galaxies: nuclei — quasars: individual (3C 138) — radio continuum: galaxies — techniques: interferometric

1. INTRODUCTION

The compact steep-spectrum (CSS) source 3C 138 ($m_v = 18.84; z = 0.759$) is a powerful quasar. It has a convex spectrum peaked at ~130 MHz with a steep high-frequency spectrum of 0.65 ($S_v \propto \nu^{-0.4}$), suggesting that its total flux density is dominated by the emissions from the jet and lobe components. Its arcsecond-scale radio structure consists of a core, several bright jet knots, a compact lobe to the east, and a fainter, more diffuse lobe to the west (Akujor et al. 1993 and references therein). High-resolution VLBI observations (Shen et al. 2001; Cotton et al. 2003) have revealed at least three compact components within the central core region. The exact location of the real core in 3C 138, however, remains uncertain. This is mainly a result of the lack of high-resolution spectral information on two possible candidates (components A and B in Cotton et al. 2003). From their earlier brightness measurements of two components, Fanti et al. (1989) claimed that component B, which is bright and compact, would be associated with the central engine. Based on the very weak linear polarization (<0.4%) in component A compared to a peak polarized intensity of 3.5% for component B at 5.0 GHz (Cotton et al. 1997) and the lower time variability in component B over ~12 yr (Shen et al. 2001), it is argued that the western end, component A, is the most likely location of the nuclear activity.

In this paper, we present the results of the core identification using the spectral data obtained from the first quasi-simultaneous multifrequency VLBI imaging of 3C 138.

2. OBSERVATIONS AND DATA REDUCTION

Observations were made using the NRAO Very Long Baseline Array (VLBA) on 2001 August 20. With the capability of frequency switching, 3C 138 was observed at four frequency bands: the dual frequency (2.3/8.4 GHz), 5.0 GHz, and 15.4 GHz. Observations at different frequencies were interlaced to ensure comparable ($u, v$) coverage at each band, with total observing times of 130, 130, and 250 minutes at dual 2.3/8.4, 5.0, and 15.4 GHz, respectively. For each scan, data were recorded in 1 bit sampling VLBA format with a total bandwidth of 64 MHz (eight 8 MHz intermediate frequency [IF] channels) per circular polarization at each station. For the dual frequency (2.3/8.4 GHz) scans, the right-circular polarized (RCP) radio signals were recorded simultaneously with four 8 MHz channels for both 2.3 and 8.4 GHz. The left-circular polarized (LCP) signals were recorded in all eight IFs for scans at both 5.0 and 15.4 GHz.

The data correlation was made at the VLBA correlator in Socorro, New Mexico. All of the postcorrelation data reduction was carried out within the NRAO AIPS (Schwab & Cotton 1983) software and the Caltech DIFMAP (Shepherd 1997) package. A priori visibility amplitude calibration was done using the antenna gain and the system temperature measured at each station. The global fringe fitting was successfully performed for observations at four frequencies: 2.3, 5.0, 8.4, and 15.4 GHz. To minimize the smearing effects on the large-field (~400 mas) imaging, fringe-fitted data were averaged to 20 s in time, and over each 8 MHz IF in frequency, in the process of the commonly used self-calibration iteration. As a result, high-resolution VLBI images of 3C 138 (including both the extended emission from the hot spots and jet knots and the compact emission from the central core region) were made at frequencies 2.3, 5.0, and 8.4 GHz (Fig. 1). The first 15.4 GHz VLBI image of 3C 138 only shows the central compact core emission (Fig. 2) because the large-scale structure is heavily resolved.

3. RESULTS

3.1. Structure

It can be seen from Figure 1 (left panels) that the large-scale structure of 3C 138 observed at three different frequencies is very similar. It consists of two distinct emission regions at two ends, which are separated by ~400 mas along a position angle of 70°, with some discrete jet knots seen in between. These jet knot components are heavily resolved, with more diffuse emissions recovered at lower frequency. These agree very well with...
the existing VLBI images. The misplacement or absence of some knots at one or two frequencies are treated as artifacts mainly due to the complex structure of the source emission at this scale. The counterjet emission at $\approx 250$ mas west of the compact core seen by 1.7 GHz VLBI observations (Cotton et al. 1997) was not detected in our observations, which is consistent with the nondetection results from past 5.0 GHz VLBI observations (Shen et al. 2001; Cotton et al. 2003).

In the central 10 mas core region, in addition to the previously reported three components (e.g., Shen et al. 2001), a new component was consistently seen at 5.0, 8.4, and 15.4 GHz in 2001 August (Figs. 1 and 2). This can be identified with the component B2 that appears on the 5.0 GHz linear polarization images (Cotton et al. 2003) in three epochs from 1998 September to 2002 October.

### 3.2. Spectrum and Core Identification

For the first time, the four central components A, B1, B2, and C (after Cotton et al. 2003) were seen at four frequencies
TABLE 1

| Component | S (Jy) | r (mas) | θ (deg) | a (mas) | $T_B$ (K) |
|-----------|-------|--------|--------|-------|---------|
| A......... | 0.053 | 0.00   | ...    | 2.33  | 4.0 $\times 10^9$ |
| B......... | 0.278 | 5.19   | 88.5   | 2.35  | 2.0 $\times 10^8$ |
| C......... | 0.054 | 9.47   | 94.0   | 2.50  | 3.5 $\times 10^9$ |
| $\nu = 2.3$ GHz$^a$ |

| A......... | 0.038 | 0.00   | ...    | 0.94  | 3.7 $\times 10^8$ |
| B1........ | 0.044 | 4.30   | 96.0   | 1.36  | 2.0 $\times 10^9$ |
| B2........ | 0.128 | 6.01   | 87.9   | 0.99  | 1.1 $\times 10^8$ |
| C......... | 0.040 | 9.43   | 96.7   | 2.80  | 4.4 $\times 10^8$ |
| $\nu = 5.0$ GHz$^a$ |

| A......... | 0.030 | 0.00   | ...    | 0.43  | 4.9 $\times 10^8$ |
| B2........ | 0.035 | 4.58   | 94.5   | 1.27  | 6.6 $\times 10^8$ |
| B1........ | 0.088 | 6.20   | 88.4   | 0.70  | 5.4 $\times 10^7$ |
| C......... | 0.025 | 9.24   | 97.0   | 2.75  | 1.0 $\times 10^9$ |
| $\nu = 8.4$ GHz$^a$ |

| A......... | 0.027 | 0.00   | ...    | 0.27  | 3.4 $\times 10^8$ |
| B2........ | 0.024 | 4.93   | 94.3   | 1.62  | 8.3 $\times 10^7$ |
| B1........ | 0.067 | 6.36   | 89.9   | 0.44  | 3.2 $\times 10^8$ |
| C......... | 0.011 | 9.51   | 99.6   | 1.47  | 4.7 $\times 10^8$ |
| $\nu = 15.4$ GHz$^a$ |

Note.—$S$: the flux density in Jy; ($r$, $\theta$): the distance and position angle of each component with respect to component A in milliarcseconds and degrees, respectively; $a$: the diameter (FWHM) of circular Gaussian component in mas; $T_B$: the brightness temperature in the source rest frame in K.

$^a$ The frequency corresponding to the following model components.

...quasi-simultaneously. This removes any time variation in the structure and makes it possible to estimate the component’s spectral index, which can be used to clarify the core identification. The quantitative description of the source structure in the central 10 mas was determined by model fitting to the calibrated visibility data at each frequency. The results are tabulated in Table 1. The first column is the component designation, and subsequent columns include the component’s flux density in Janskys; separation and position angle of each component with respect to component A, in milliarcseconds and degrees, respectively; the size (FWHM) of the circular Gaussian component, in milliarcseconds; and the component’s brightness temperature in the source rest frame.

Again, this is flatter than that of 0.59 for another candidate (component B). This suggests that component A is the nuclear component. Components B1 and B2 have almost the same spectral indices, 0.57 and 0.54, respectively, suggesting the same origin of, or environment in, both components. Thus, it is very unlikely that either B1 or B2 was the location of the central engine. Our core identification is further supported by the measured brightness temperature $T_B$ (see Table 1). Component A has the highest $T_B$, 3.4 $\times 10^8$ K at 15.4 GHz, which almost remains unchanged at other lower frequencies, while both B1 and B2 see a decrease in $T_B$ with the frequency. This identification is consistent with the results from the studies of the linear polarization (Cotton et al. 1997, 2003) and variability (Shen et al. 2001). Component C is a typical jet component with a spectral index of 1.15 between 5.0 and 15.4 GHz. For comparison, we also calculated the spectral index $\alpha$ of 0.53 GHz for both lobe emission at the eastern end of the central core region (see Fig. 1), based on their integrated flux densities estimated from the images at 2.3, 5.0, and 8.4 GHz. They are eventually the same as about 1.5.

To ensure an accurate absolute flux density calibration at all the observing frequencies, a strong compact quasar PKS 0528+ 134 was observed as a flux density calibrator during our VLBA observations of 3C 138. The comparison between the total flux density measurements at 5.0, 8.4, and 15.4 GHz by the University of Michigan Radio Astronomy Observatory (UMRAO) and at 2.3 GHz by the NRAO Green Bank Interferometer (GBI), and the integrated flux densities in the VLBA images, indicates that the errors in the absolute flux density calibration are about 3%, 5%, 2%, and 10% at frequencies of 2.3, 5.0, 8.4, and 15.4 GHz, respectively (H.-B. Cai et al. 2005, in preparation). In addition, there are typical 10% errors in the flux density, caused by the Gaussian model fitting. Taking into account the overall error budgets due to these effects in the spectral fitting, we obtained $\alpha$ of 0.38 $\pm$ 0.09 and 0.60 $\pm$ 0.09 for components A and B, respectively, supporting the core identification discussed above.

For component C, there must be an absorption at 2.3 GHz in order to fit in the spectral shape between 4.8 and 15.4 GHz. The mechanism for the absorption could be the intrinsic synchrotron self-absorption (SSA) or the free-free absorption (FFA) by the ambient cold plasma. Both can produce convex spectra $S_\nu \propto \nu^{-2.5}$ [1 − exp ($-\tau_f \nu^{-(2.5+\alpha)}$)] for SSA, and $S_\nu \propto \nu^{-\alpha}$ [exp ($-\tau_f \nu^{-(2.5+\alpha)}$)] for FFA, where $\nu$ is the observing frequency in GHz, $\tau_s$ and $\tau_f$ are...
the SSA and FFA coefficients at 1 GHz, respectively, and \( \alpha \) is the spectral index. Either of the two models (SSA and FFA) can fit the observed convex spectrum of component C quite well. With a fixed spectral index \( \alpha = 1.2 \) (see Table 2), the fitted 1 GHz absorption coefficients and synchrotron flux density are \( \tau = 32 \) and \( S_0 = 8.6 \) mJy, and \( \tau_f = 4.3 \) and \( S_0 = 300 \) mJy for SSA and FFA, respectively. For the SSA model, the fitted spectrum has a peak flux density of 59 mJy at a turnover frequency of 2.8 GHz. This would require a very large magnetic field within component C of about 35 G, which is unrealistic for component C to maintain its synchrotron emission for years against synchrotron loss (Kellermann & Pauliny-Toth 1981). However, the nondetection of any polarized emission in the inner jet component C is consistent with component C being surrounded by a patchy but dense medium (Cotton et al. 2003). Thus, it is very likely that the observed absorption in component C is mainly due to FFA by the ambient cold dense plasma.

### 3.3. Proper Motion

Previous studies have detected superluminal motions in the central core region of 3C 138 (Shen et al. 2001; Cotton et al. 2003). To avoid any possible position offset among the measurements made at different frequencies, only 5.0 GHz data (including our new observations) were used to refine the proper motion calculations. Data points at epochs 1985.50, 1989.72, and 1997.85 are from Shen et al. (2001). Data points at epochs 1994.97, 1997.60, 1998.70, 2000.59, and 2002.79 are from Cotton et al. (2003). The data point at epoch 2001.64 is from this work which has well resolved component B into components B1 and B2. By assuming that the position of component B is at the weighted center of two components (B1 and B2), with weights proportional to their flux densities, we can obtain the position of component B from model fitting results of components B1 and B2 at epoch 2001.64.

As shown in Figure 4, there is no significant change in the speed of motion in either component B (in \( \approx 18 \) yr) or component C (in \( \approx 8 \) yr) with respect to component A, which is assumed to be stationary as the location of the nucleus. The best-fit proper motion is \( 0.072 \pm 0.010 \) and \( 0.20 \pm 0.03 \) mas yr\(^{-1} \), corresponding to apparent superluminal speeds of \( 2.6 \pm 0.4 \) c and \( 7.2 \pm 1.0 \) c for components B and C, respectively (assuming \( H_0 = 65 \) km s\(^{-1} \) Mpc\(^{-1} \) and \( q_0 = 0.5 \)). This is consistent with the published estimate of 3.3c for component B (Shen et al. 2001). Component C, which is farther away than component B from the nucleus component A, has a much faster motion than component B. This could be due to (re)acceleration or a smaller viewing angle of its emission to the observer’s line of sight.

The new component B2 (see Figs. 1 and 2) was first clearly detected in a linear polarization image in September 1998 (Cotton et al. 2003). Since then, both components B1 and B2 have been consistently seen in another two epochs of high-resolution polarization-sensitive VLBA observations by Cotton et al. (2003). The inset of Figure 4 is a plot of the separations between components B1 and B2 as a function of the observing epochs. Three data points denoted by open circles are estimated from the polarized images (Cotton et al. 2003), and the data point represented by a star is from our total intensity measurement (see Table 1).

![Figure 4](image)

**Fig. 4.—** Separations of component B (filled squares) and component C (filled circles) relative to component A. Two lines represent the best-fit proper motions of \( 0.072 \pm 0.010 \) and \( 0.20 \pm 0.03 \) mas yr\(^{-1} \) for components B (solid line) and C (dotted line). Inset is a plot of separation between components B1 and B2 as a function of the observing epoch; also shown is a fitting line (dashed line) with a slope of \( -0.009 \pm 0.015 \) mas yr\(^{-1} \) (see text). All these measurements were made from total intensity data at 5.0 GHz.

### 4. DISCUSSION

The main results of this work are summarized in the abstract, so we avoid redundancy here. It should be noted that all the arguments on the core identification are based on an underlying assumption that the central engine must be associated with one of the detected components. However, this may not be the case for CSS sources, whose emission is usually dominated by the strong knot/lobe/jet emissions. It is proposed (Fanti et al. 1995; Readhead et al. 1996) that CSS sources are part of evolutionary sequence, representing an early stage between the compact symmetric objects and large Fanaroff-Riley type II objects. The true
core of 3C 138, which is a prototype of a CSS source, could be too weak to be seen or simply embedded in the surrounding dense medium. If so, the exact location of the center of activity in 3C 138 still remains undetected.

The phase-referenced VLBI observations can provide precise positional information with respect to the external reference source with sub-milliarcsecond accuracy. By examining the component’s absolute proper motion relative to the more distant compact reference source (Bartel et al. 1986), one can confirm or exclude the presumed location of the center of activity dynamically.

During our VLBA observations at 15.4 GHz, the phase-referencing technique was also adopted by fast switching between 3C 138 and the nearby (in angular separation) but distant ($z = 2.07$) bright compact quasar PKS 0528+134, with an observing cycle time of 100 s, consisting of 32 s on PKS 0528+134, 8 s for antenna slewing, 52 s on 3C 138, and another 8 s for antenna slewing. This turned out to be successful with components A and B, which are well detected (Shang et al. 2004). With future observations of more epochs, we will be able to explore the possibility that none of these visible components is the true core.

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