LARGE-SCALE REGULAR MORPHOLOGICAL PATTERNS IN THE RADIO JET OF NGC 6251

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ABSTRACT

We report on large-scale regular morphological patterns found in the radio jet of the nearby radio galaxy NGC 6251. Investigating morphological properties of this radio jet from the nucleus to a radial distance of \( \sim 300'' \) (\( \sim 140 \text{ kpc} \)) mapped at 1662 MHz and 4885 MHz by Perley, Bridle, & Willis, we find three chains, each of which consists of five radio knots. We also find that eight radio knots in the first two chains consist of three small subknots (the triple-knotty substructures). We discuss the observational properties of these regular morphological patterns.

Key words: galaxies: active — galaxies: individual (NGC 6251) — galaxies: jets — radio continuum

1. INTRODUCTION

Since the discovery of the powerful radio jet from quasar 3C273 (Hazard, Mackey, & Shimmins 1963; see for a review Bridle & Perley 1984; Zensus 1997), the generation of radio jets has been one of the long-standing main problems in active galactic nuclei (e.g., Begelman, Blandford, & Rees 1980; Urry & Padovani 1995). The most probable energy sources have been considered to be either mass-accreting, supermassive, single black holes around which gravitational energy is transformed into huge kinetic and radiation energies with the help of gaseous accretion disks (e.g., Rees 1984) or the electromagnetic extraction of energy from spinning supermassive black holes (Blandford & Znajek 1977; see also Wilson & Colbert 1995). To understand the genesis of radio jets, it is important to find some reliable observational constraints on theoretical models.

It has been noted that parsec-scale radio jets probed by VLBI techniques often show wiggles (e.g., Whitmore & Mateas 1981; Roos 1988; Roos, Kaasta, & Hummel 1993). If a certain mechanism responsible for the formation of the wiggles (e.g., the precession of a supermassive black hole binary; Begelman, Blandford, & Rees 1980) has been working since the onset of radio-jet activity, there could be some morphological evidence even in well-developed (i.e., \( \sim 100 \text{ kpc} \) scale) radio jets. Furthermore, recent progress in three-dimensional numerical MHD simulations has enabled us to examine the detail of morphological properties of radio jets due to the so-called Kelvin-Holmeltz instability in the magnetic fluid (e.g., Rosen et al. 1998; Koide, Shibata, & Kudoh 1999). Therefore, since morphological properties of actual radio jets provide important constraints on the physical process involved in radio jets, it is interesting to investigate overall morphological properties of some well-developed radio jets in detail.

For this purpose, we investigate morphological properties of the radio jet of NGC 6251 in detail because the radio jet of NGC 6251 is one of the brightest known examples of a well-developed jet (Waggetter, Warner, & Baldwin 1977; Cohen & Readhead 1979; Perley, Bridle, & Willis 1984; Jones et al. 1986; Jones & Wehrle 1994). We use a distance to NGC 6251, 94.4 Mpc, that is determined with the use of a recession velocity of NGC 6251 to the galactic standard of rest, \( V_{\text{GRS}} = 7079 \text{ km s}^{-1} \) (de Vaucouleurs et al. 1991), and Hubble constant \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).
increasing distance, although some scatter in the data points can be seen.

Another interesting property found in Figure 1 is that the separations between the knots appear to be larger for the outer chain. In Figure 6, we show the separations \( (s) \) between adjacent knots in each chain. The separations increase from chain A through B to C. It is also found that the variation patterns in \( s_{i}(i+1)-i \) from \( i = 1 \) to \( 4 \) are quite similar among the three chains. These findings support the conclusion that our identifications of three chains are really meaningful. It is thus suggested that the radio-jet activity in NGC 6251 is not sporadic but regular with some periodicity.

2.2. Substructures in Radio Knots

We further investigate detailed morphological properties of the knots.

![Fig. 1. Top, radio continuum image at 4885 MHz obtained by Perley, Bridle, & Willis (1984); bottom, chains A, B, and C together with their radio knots.](image)

![Fig. 2. Definitions of the quantities used in this paper (see text).](image)

![Fig. 3. Angular distances (d) of the 15 knots plotted against the sequential knot number.](image)

| Sequential No. (1) | Name (2) | \( d \) (arcsec) (3) | \( D \) (kpc) (4) | \( s \) (arcsec) (5) | \( S \) (kpc) (6) | \( w \) (arcsec) (7) | \( W \) (kpc) (8) |
|-------------------|---------|-----------------|----------------|-----------------|----------------|--------------------|----------------|
| 1                 | A1      | 5.8             | 3.6            | ...             | ...            | ...                | ...            |
| 2                 | A2      | 13.5            | 8.4            | 7.7             | 4.8            | ...                | ...            |
| 3                 | A3      | 24.8            | 15.5           | 11.3            | 7.1            | ...                | ...            |
| 4                 | A4      | 32.8            | 20.5           | 8.0             | 5.0            | ...                | ...            |
| 5                 | A5      | 51.7            | 32.4           | 18.9            | 11.9           | ...                | ...            |
| 6                 | B1      | 72.6            | 45.5           | ...             | 66.8           | 41.8               | ...            |
| 7                 | B2      | 85.8            | 53.7           | 13.2            | 8.3            | 72.3               | 45.3           |
| 8                 | B3      | 101.6           | 63.6           | 15.8            | 9.9            | 76.8               | 48.1           |
| 9                 | B4      | 111.3           | 69.7           | 9.7             | 6.1            | 78.6               | 49.2           |
| 10                | B5      | 140.2           | 87.8           | 28.9            | 18.1           | 88.5               | 55.4           |
| 11                | C1      | 192.7           | 120.7          | ...             | 120.1          | 75.2               | ...            |
| 12                | C2      | 208.8           | 130.8          | 16.2            | 10.1           | 123.1              | 77.1           |
| 13                | C3      | 228.5           | 143.1          | 19.6            | 12.3           | 126.9              | 79.5           |
| 14                | C4      | 243.5           | 152.5          | 15.0            | 9.4            | 132.1              | 82.8           |
| 15                | C5      | 271.2           | 169.9          | 27.7            | 17.3           | 131.0              | 82.1           |

**TABLE 1**

**Basic Data of the Identified Knots**
of the individual radio knots. To perform this, we use the radio continuum image at 1662 MHz given by Perley et al. (1984; see their Fig. 4). This map covers the inner 2′ (≈ 55 kpc) region of the radio jet with spatial resolution 1.15″. In Figure 7, we show this map together with close-up images of eight individual knots; the first four knots (A2, A3, A4, and A5) are in chain A and the remaining four knots (B1, B2, B3, and B4) are in chain B. These identifications are the same as those in § 2.1 (see Table 1). Each knot appears to consist of three brightness peaks, the triple-knotty substructure. In particular, this substructure is unambiguously seen in the first two knots, A2 and A3.

3. DISCUSSION

We have shown that there are two kinds of regular morphological structures in the radio jet of NGC 6251 (1) three chains consisting of five radio knots each and (2) the triple-knotty substructures in the individual knots. Here we discuss some possible origins of these large-scale regular structures.

3.1. Chains

The presence of three chains suggests that a certain periodicity is involved in the radio-jet activity of NGC 6251. As shown in Table 1, the separations ($W_i$) of the ith knots on two adjacent chains are quite similar between adjacent chains; i.e., the average values are $W(A-B) \approx 48.0 \pm 0.5$ kpc and $W(B-C) \approx 79.3 \pm 2.9$ kpc. We estimate timescales corresponding to these separations. To perform this, both the viewing angle toward the jet ($\theta_{\text{jet}}$) and the jet velocity ($v_{\text{jet}}$) are necessary for the kiloparsec-scale radio jet.

Since the parsec-scale counterjet cannot be seen in the previous VLBI observations (Perley et al. 1984; Jones et al. 1986; Jones & Wehrle 1994; see, however, Sudou et al. 2000a, 2000b), it is unlikely that the radio jet of NGC 6251 lies close to the celestial plane. Jones et al. (1986), based on the observed jet-to-counterjet intensity ratio, estimate that the angle between the radio jet and our line of sight may be $\theta_{\text{jet}} \approx 45°$. We therefore adopt $\theta_{\text{jet}} = 45°$ in later analysis. Another important quantity is the large-scale (i.e., kiloparsec-scale) jet velocity $v_{\text{jet}}$, which is also difficult to estimate (e.g., Perley et al. 1984). Based on several constraints (e.g., the energy flux required to power the radio jet), Perley et al. (1984) suggest that the large-scale jet velocity of NGC 6251 is subrelativistic: $v_{\text{jet}} \lesssim 0.1c$. It is known that ram pressure confinement for the strongest double-lobed radio sources such as NGC 6251 requires $v_{\text{jet}} \approx 0.1c$ (e.g., Begelman et al. 1984). On the other hand, using the observed jet-to-counterjet brightness ratio, Jones et al. (1986) suggests $v_{\text{jet}} \cos \theta_{\text{jet}} \geq 0.6$ for a brightness ratio $\geq 80$. Given $\theta_{\text{jet}} = 45°$, they obtain $v_{\text{jet}} \approx 0.84c$. Since this estimate seems more reliable, we adopt for simplicity $v_{\text{jet}} = 0.8c$ in later analysis. These assumptions (i.e., $\theta_{\text{jet}} = 45°$ and $v_{\text{jet}} = 0.8c$) seem enough to estimate rough timescales.
related to the large-scale regular structures found in this study.

First we estimate timescales related to the three chains, A, B, and C. Since the jet velocity is relativistic, we have to take account of the relativistic aberration effect. The true projected distance of the radio jet from the nucleus is estimated as $D_{\text{jet}} = \delta D_{\text{jet}}$, where $\delta$ is the Doppler factor defined as $\delta = 1/\gamma[1 - (v_{\text{jet}}/c) \cos \theta_{\text{jet}}]$, where $\gamma = [1 - (v_{\text{jet}}/c)^2]^{-1/2}$. Thus the true length of the radio jet is estimated as $L_{\text{jet}} = D_{\text{jet}}/\sin \theta_{\text{jet}}$. Therefore, the related timescale $\tau_{\text{jet}}$ is estimated as

$$\tau_{\text{jet}} = L_{\text{jet}}/v_{\text{jet}} = D_{\text{jet}}/\gamma (0.8c \sin \theta_{\text{jet}}),$$

$$\simeq 1.83 \times 10^{11} \delta D_{\text{jet},1} v_{\text{jet},0.8}/\sin \theta_{\text{jet},45} \text{ s},$$

$$\simeq 5.79 \times 10^{3} \delta D_{\text{jet},1} v_{\text{jet},0.8}/\sin \theta_{\text{jet},45} \text{ yr},$$

where $D_{\text{jet},1}$ is the jet length projected onto the celestial plane in kiloparsecs, $v_{\text{jet},0.8}$ is the jet velocity in units of 0.8$c$, and $\theta_{\text{jet},45}$ is the jet-viewing angle in units of 45°. Given the velocity and viewing angle assumed above, we obtain $\delta = 1.38$. The projected jet lengths of the three chains are $D_{\text{jet}}(A) = D_{A}(A) - D_{A}(A) = 32.4 - 3.6 = 28.8$ kpc, $D_{\text{jet}}(B) = D_{B}(B) - D_{B}(B) = 87.8 - 45.5 = 42.3$ kpc, and $D_{\text{jet}}(C) = D_{C}(C) - D_{C}(C) = 169.9 - 20.7 = 49.2$ kpc. Then we obtain the durations required to develop the radio jet for the three chains: $\tau_{\text{jet}}(A) \approx 2.3 \times 10^5$ yr, $\tau_{\text{jet}}(B) \approx 3.4 \times 10^5$ yr, and $\tau_{\text{jet}}(C) \approx 3.9 \times 10^5$ yr. These durations are shorter by 1 order of magnitude than the precession period estimated by Jones et al. (1986; see also Begelman et al. 1980), $\tau_{\text{prec}} \simeq 1.8 \times 10^6$ yr. This precession is proposed to explain the global wiggle pattern of the radio jet of NGC 6251.

As estimated above, the length of each chain becomes longer with increasing radial distance; i.e., $D_{\text{jet}}(A) < D_{\text{jet}}(B) < D_{\text{jet}}(C)$. If this tendency is real, the radio jet of NGC 6251 must be accelerated, even at several tens of kiloparsec. An alternative explanation may be that the radio jet is bending in a plane that contains the radio jet and our line

![Radio continuum image at 1662 MHz obtained by Perley et al. (1984) of chain A (top) and chain B (middle) and close-up images of the eight radio knots (bottom). Arrows show resolved substructure of the knots.](image)

Fig. 7.—Radio continuum image at 1662 MHz obtained by Perley et al. (1984) of chain A (top) and chain B (middle) and close-up images of the eight radio knots (bottom). Arrows show resolved substructure of the knots.
of sight to the jet. Since the position angle of the parsec-scale radio jet (P.A. = 302.2° ± 0.8° for epoch 1950.0; Cohen & Readhead 1979) is slightly different from that of the kiloparsec-scale jet (P.A. = 296.5°; Waggett et al. 1977), Cohen & Readhead (1979) suggest a possible bending of the radio jet of NGC 6251. Therefore, it is interesting to investigate this idea in more detail.

Here we assume that the true jet lengths of the three chains are nearly the same and that the observed differences among them are attributed to the differences in the viewing angle toward them. If this is the case, we obtain the following relation:

\[
\frac{D_{\text{jet}}(A)\delta(A)}{\sin \theta_{\text{jet}}(A)} = \frac{D_{\text{jet}}(B)\delta(B)}{\sin \theta_{\text{jet}}(B)} = \frac{D_{\text{jet}}(C)\delta(C)}{\sin \theta_{\text{jet}}(C)},
\]

where \(\theta_{\text{jet}}(A), \theta_{\text{jet}}(B), \) and \(\theta_{\text{jet}}(C)\) are the average viewing angles toward chain A, B, and C, respectively, and \(\delta(A), \delta(B),\) and \(\delta(C)\) are the average Doppler factors toward chain A, B, and C, respectively. If we adopt \(\theta_{\text{jet}}(C) = 45.0°\) and \(\delta(C) = 1.38\), we obtain \(\theta_{\text{jet}}(A) \approx 33.1°\) and \(\theta_{\text{jet}}(B) \approx 41.3°\), with \(\delta(A) \approx 1.82\) and \(\delta(B) \approx 1.50\). It is therefore suggested that the direction of the radio jet is approaching the line of sight as time goes by or that the jet flow follows a fixed but bent path. This result is schematically illustrated in Figure 8.

Recently, Sudou et al. (2000a, 2000b) have found the counterjet at subparsec scale and estimated the viewing angle to the subparsec scale jet as \(\theta_{\text{jet}} \approx 17°-31°\). Since the viewing angle toward chain A derived above is consistent with their new estimate, this bending-jet model appears consistent with the observation. Therefore, it is not necessary to introduce the jet acceleration at kiloparsec regions.

### 3.2. Knots in Chains

We investigate the separations of the knots in the three chains. An average separation of the knots in each chain is \(S = \sum_{i=1}^{n} S_{(i+1)-i}/4 \approx 7.2 ± 2.9\) kpc for chain A, 10.6 ± 4.5 kpc for chain B, and 12.3 ± 3.1 kpc for chain C. Therefore, the average separation appears to increase from chain A to chain B to chain C. It is noted that the fifth knot in each chain is located at a larger distance than that expected from the separations for the remaining four knots (see column 5 of Table 1). If we omit the data of the fifth knot, we obtain average separations of \(S = \sum_{i=1}^{n} S_{(i+1)-i}/3 \approx 5.6 ± 1.0\) kpc for chain A, 8.1 ± 1.6 kpc for chain B, and 10.6 ± 1.2 kpc for chain C. Although the tendency holds, the average separations are smaller than the former estimates, respectively. If we adopt the bending-jet model described in §3.1, together with the relativistic aberration effect, the true separations, \(S^0 = \delta S/\sin \theta_{\text{jet}}\), are \(S^0(A) \approx 5.6 \times 1.82/\sin 33.1° \approx 18.7\) kpc, \(S^0(B) \approx 8.1 \times 1.50/\sin 41.3° \approx 18.4\) kpc, and \(S^0(C) \approx 10.6 \times 1.38/\sin 45° \approx 20.7\) kpc. These values are similar to each other. We obtain an average separation of the knots in the three chains of \(\approx 19.2\) kpc, corresponding to a timescale of \(\approx 7.8 \times 10^4\) yr, given the jet velocity \(v_{\text{jet}} = 0.8c\).

### 3.3. Triple-Knotty Substructure

We discuss briefly observational properties of the triple-knotty substructures. As shown in Figure 7, the first two knots (A2 and A3) show a clear triple-knotty substructure. However, the other knots show a range of irregular, complex morphologies, although we give possible identifications of the triple-knotty substructures for these by arrows. It is interesting to mention that such a triple-knotty substructure is also found in the radio jet of Centaurus A (Clarke, Burns, & Feigelson 1986).

### 3.4. Concluding Remarks

In summary, the large-scale regular morphological patterns involve three kinds of structures: chains, knots, and triple-knotty substructures in the knots. The corresponding timescales for the first two structures are \(\sim 10^7\) yr and \(\sim 10^4\) yr, respectively. Although the longest timescale obtained for the chains may be related to the precession motion, the other two timescales are not understood easily.

Although some studies of the large-scale morphological properties of the radio jets have been carried out (e.g., Perley et al. 1984; Sparks, Biretta, & Macchetto 1996; Perlman et al. 1999; Biretta, Sparks, & Macchetto 1999; Bahcall et al. 1995; Röser, Conway, & Meisenheimer 1996; Clarke et al. 1986), the analysis presented in this paper is the first trial to investigate large-scale morphological regularity of radio jets. Since this kind of analysis needs high-resolution and large-scale radio continuum mapping, it seems difficult to perform a systematic morphological study of radio jets. Therefore, at present, it is difficult to judge whether or not large-scale morphological patterns found in the radio jet of NGC 6251 are general properties. However, this kind of analysis will be important to provide observational constraints on the theory of radio jets.
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