# Bi-periodic variation in the BL Lac AO 0235+164

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**Abstract.**
High resolution VLBI hybrid map of the BL Lacertae object AO 0235+164 has been produced at a wavelength of 6 cm. The map shows that the object's radio structure is dominated by a strong, nearly unresolved core with a weak and clear component in northeast direction and a faint one in southwest direction. The positional angle of its jet component are equal to 66.4°, which is the biggest one in comparison with previous results. Based on the variation of its flux density with time at three different frequencies, we find that the flux density of AO 0235+164 shows bi-periodic variation, i.e., the shorter periodic variation of $\sim 1.81$ years and a longer periodic variation of $\sim 3.63$ years. The later is essentially in agreement with our earlier predicted results that the existence of the periodic variation of $\sim 3.63$ years may be caused by the precession of its 'central engine'. This bi-periodic variation is probably the results of the joint action of jet outbursts and jet rotation. With the binary black hole models of Kaastra & Roos, we get the minimum total mass of the binary system of $1.46 \times 10^8 M_\odot$.

**Keywords:** (galaxies:) BL Lacertae objects: individual ( AO 0235+164 ), techniques: image processing

## 1. Introduction

The very compact, flat spectrum radio source AO 0235+164 was discovered in Arecibo occultation observations by C. Hazard and J. Sutton and was identified with a BL Lacertae object (Spinrad & Smith 1975), which is active in nearly all wavelengths. The amplitude of its variability is about 3 – 4 times of the quiescent flux density in radio, and up to 100 times of the quiescent flux density in optical wavelengths. The timescale of its variability ranges from months at low frequencies (Wolfe et al. 1978) to weeks at high frequencies (Macleod et al. 1976), and to days at optical wavelengths (Saust 1992). Observations in X-ray and $\gamma$-ray wavelengths also reveal violent variations of its flux density with time (Madejski et al. 1996). This makes AO 0235+164 one of the exceptional violently varying BL Lacs.

The radio spectrum of AO 0235+164 appears to be very flat. This would lead one to expect a complex, wavelength-dependent structure consisting of several components with different turnover frequencies. To one's surprise, the VLBI observed radio structure of AO 0235+164 appears surprisingly simple. High resolution VLBI observations reveal that the source has different structure at different frequencies in the radio-wavelength region. The jet positional angle varies rapidly with time, and shows a certain periodicity (Zhang et al. 1997).

The phenomenology becomes even more complex due to the fact that three redshifts have been identified in the optical spectrum of AO 0235+164—one in emission lines ($z_{em} = 0.94$), and two in absorption lines ($z_{abs} = 0.524$ and $z_{abs} = 0.857$). Except for very weak emission lines, AO 0235+164 has all the characteristics of optically violent variable (OVV) quasars (including the GeV emission). Madejski et al. (1996) suppose it may be an intermediate object between two subclasses of a larger class called " blazars "; true featureless BL Lacertae objects and OVVs.

Here we report on a new observation in section 2. The results and discussion will follow in section 3 and conclusions can be found in section 4.

## 2. Observations

The observation was conducted with a 10 station VLBI array on Feb.18, 1997 from $UT = 10^h0^m$ to $22^h0^m$. The array consisted of the telescopes listed in Table I. Unfortunately, Noto Urumqi and Jodrell bank failed, so for only 7 stations observational data was used.

Figure 1 shows the resultant (u,v) coverage. The maximum baseline length both in north-south and west-east direction were $\sim$ 120 million wavelengths. Because of lack of three stations, the (u,v) coverage of the observation is marginal, especially in the region between short and long baselines, where no sampling is present. This has some influence on our hybrid map, within which some details may be lost. Despite of the above, we can find from the subsequent results that our expected observational goal has been reached.

All seven stations observed left circular polarization in MkIII Mode B. The data was correlated at the MPIfR processor in Bonn. NRAO 150 and DA 193 were used as fringe-finding and calibrator sources. Fringe fitting was done within the NRAO AIPS programs. The station-based residual fringe rates and the residual delays were estimated with a coherent integration time of 120 seconds. Amplitude calibration was

Table I. VLBI telescopes and their characteristics at 5 GHz

| station | Diameter(m) | $T_{sys}$(K) | Sensitivity(K/Jy) |
|---|---|---|---|
| Effelsberg | 100 | 17.80 | 1.0 |
| Shanghai | 25 | 42.30 | 0.10 |
| Medicina | 32 | 52 | 0.16 |
| HartRAO | 26 | 75.10 | 0.085 |
| Onsala | 25 | 48.70 | 0.05614 |
| Westerbork | 5 × 25 | 104.4 | 1.0 |
| Torun | 32 | 31.30 | 0.16 |
| Noto | 32 | | 0.14 |
| Jodrell bank | 26 | | 0.12 |
| Urumqi | 25 | | 0.1 |

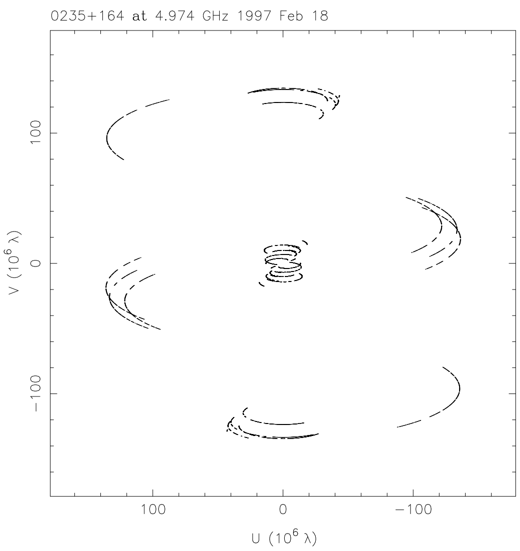


*Figure 1.* (u, v) coverage of 7-stations VLBI array at 5 GHz

done using programs ANTAB, APCAL and CLCAL. After the initial data processing was completed, the data was averaged to 45 seconds.

Since the visibility data indicated that the source was only slightly resolved, a point source model was used for the first hybrid map. During the first few iterations, we used uniform weighting and corrected only the visibility phases. Later, when model visibilities fitted fairly well to the observed visibilities, both the visibility phases and amplitudes were corrected. The final image of AO 0235+164 is shown in Figure 2.

## 3. Results and Discussion

Figure 2 is the final resultant hybrid map of radio source AO 0235+164. The total flux density of the source is 0.38 Jy. From Figure 4, we find that the source is in a radio quiescent period on epoch 1997.1.

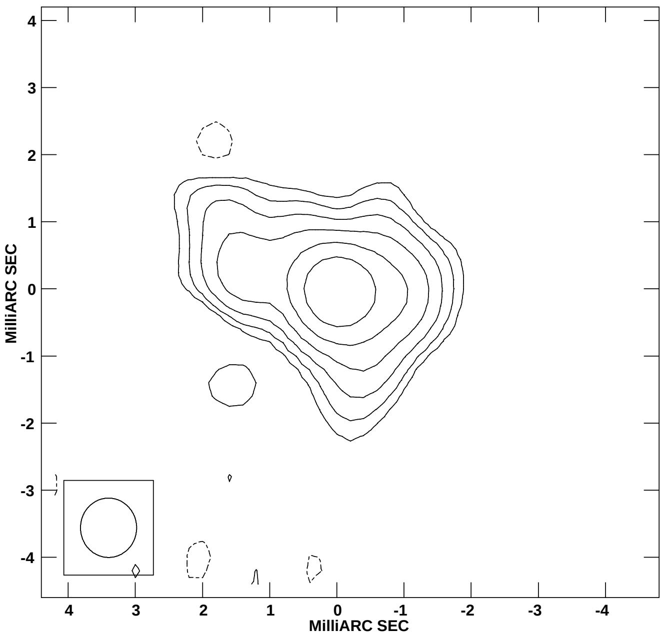


*Figure 2.* Hybrid map of AO 0235+164 at 6 cm the peak flux density is 0.13 Jy/beam; the size of clean beam is $0.88 \times 0.83$ mas with positional angle of $1.6°$, the contour levels are $1.0E-3 \times (-5, -2, 2, 4, 8, 16, 32, 64) Jy/beam$.

AO 0235+164 shows a clear core-dominated structure with a relatively obvious component in northeast direction and a fainter component in southwest direction. The previous VLBI epochs also show the presence of the faint southwest direction component, which is so weak in comparison with the northeast direction component that it was regarded as a spurious one. Yet for this observation, the total flux density is only 0.38 Jy, which is much smaller than the previous ones of over more than 1 Jy. It is possible that the southwest direction component might be always present and change very little from one epoch to another so that it appears relatively clearly when the source has extremely low total flux density.

A three component gaussian model fits our data very well. The detailed parameters of the three components are listed in Table II. In all previous VLBI observations for AO 0235+164 at 5 GHz, the jet

Table II. Model description of AO 0235+164

| Flux(Jy) | Separation(mas) | P.A.(deg) | Major Axis(mas) | Axial ratio | p.a.(deg) |
|---|---|---|---|---|---|
| 0.2918 | 0 | 0 | 0.79 | 0.75 | -60.2 |
| 0.0071 | 1.74 | 66.4 | 1.14 | 0.58 | 46.52 |
| 0.0057 | 1.60 | -125.1 | 1.29 | 0.43 | -45.0 |

structure and the direction of jet structure differs with the observation epoch. Since the interval between any two VLBI observations is long, the relation between any two epochs of jet components couldn't be clearly identified, i.e., one cannot determine if they belong to the same component at a different evolutionary stage. If we intend to calculate the apparent velocity of the jet component by measuring the displacement between any two different epochs, it is necessary to reduce the interval of two subsequent observations.

### 3.1. Periodic variation of its jet positional angle

AO 0235+164 is an extremely special milli / micro arc-second scale radio source. Not only the components of the source expand at a superluminal speed, but also its jet positional angle changes rapidly (see Table III). The positional angle in Table III were obtained at a frequency of 5 GHz except for observations at epochs 1982.9 and 1986.2 (22 GHz and 0.33 GHz respectively) (Zhang et al. 1997; Shen 1996). From the first 6 observations, a periodic variation of 3 – 5 years of

Table III. Jet positional angles of 8 epochs

| Epoch | 1979.2 | 1980.8 | 1981.9 | 1982.9 | 1983.5 | 1986.2 | 1992.9 | 1997.1 |
|---|---|---|---|---|---|---|---|---|
| P.A.(°) | $25 \pm 0.4$ | $13.8 \pm 0.6$ | $47 \pm 27$ | $6.6 \pm 0.4$ | 0 | 22 | 58 | $66.4 \pm 0.5$ |

the jet positional angle can be found (Zhang et al. 1997). A sinusoidal fitting result (Figure 3) shows also that a value of $\sim 3.5$ years can fit the first 6 value fairly well. The intervals of the last two observations are too

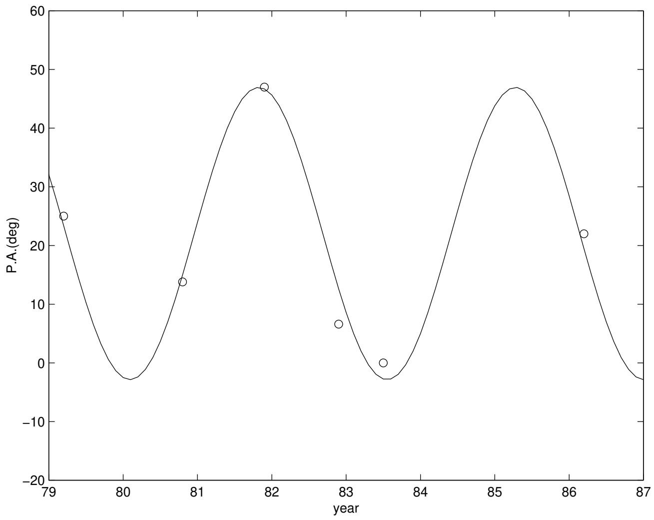


*Figure 3.* Fitting result of the variation of the jet positional angle

large to add to the precision of the variation of the jet positional angle. When we try to fit the data with a period close to 1.8 years (about half value of 3.5 years ), the fitting result is worse in comparison with that of $\sim 3.5$ years. Although we believe that there exists many other shorter periods which can fit the data well, they would become more and more incredible as the periods become shorter.

### 3.2. Relationship between the variations of the flux density and the jet positional angle of AO 0235+164

For the past two decades the 26-meter telescope of UMRAO has been dedicated to the study of total flux density from active extragalactic objects in the radio-wavelength region. AO 0235+164 is one of the sources which have been observed at 5 GHz, 8 GHz and 14.5 GHz over 20 years. The variation of the total flux density with time at three different frequencies is shown in Figure 4, which shows the variation of the flux density at higher frequency occurs earlier than that at lower frequency. This implies that the radiating region at higher frequencies is closer to the central engine than that at lower frequencies, as has been described in many papers (e.g., Melia et al. 1989; Jiang et al. 1998 ). Following such an morphology, certain factors, whether they are propagation of shock waves or the outflow of matter or both of

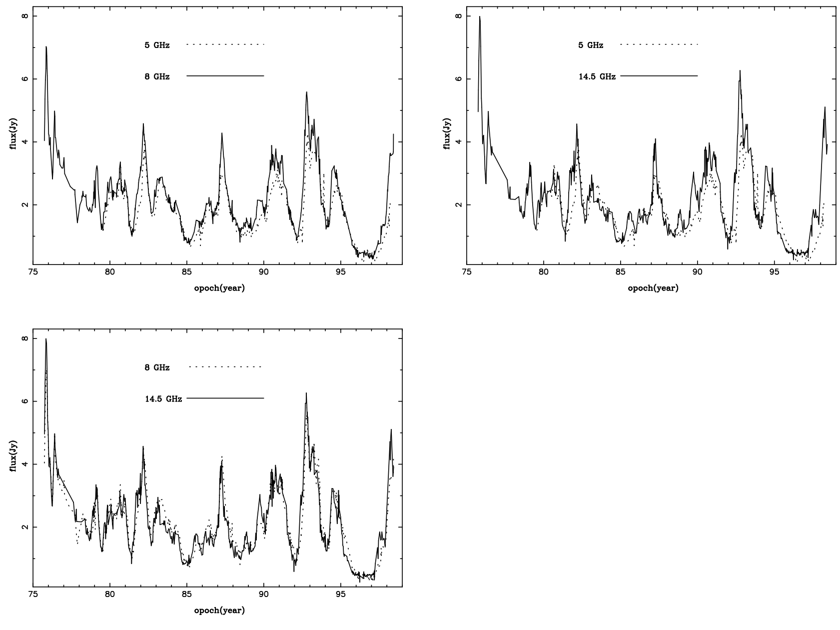


*Figure 4.* Flux density history at (a): 5 GHz, (b): 8GHz and (c): 14.5 GHz measured at UMRAO

them, act on the jet and spread down along the jet, in good agreement with the unified scheme of AGN.

The monitoring result of the flux density at 3.6 cm of AO 0235+164 (Chu, et al. 1996) shows that, the timescale of jet outbursts of the source is about a little more than one year, far less than the timescale of 3 – 5 years of its jet positional angle variation (Zhang et al. 1997). Figure 4 also shows the presence of two possible periodic variation of its flux density with time, i.e., a shorter periodic variation of 1 – 2 years and a longer periodic variation of 3 – 5 years. In order to specifically determine the values of these periods, the method of analysis of the expected mean square deviation (Jurkevich 1971) is used to search for the periods of the variations.

By virtue of the well known theorem on the addition of variances, Jurkevich (1971) proposes that a data sample is divided into several groups according to the phase of each data point, and when the trial period is equal to the true period, the sum of the variances of all groups will reach its minimum. The $V^2$ – P curve at the three different frequencies is shown in Figure 5 and the resultant values of the periods

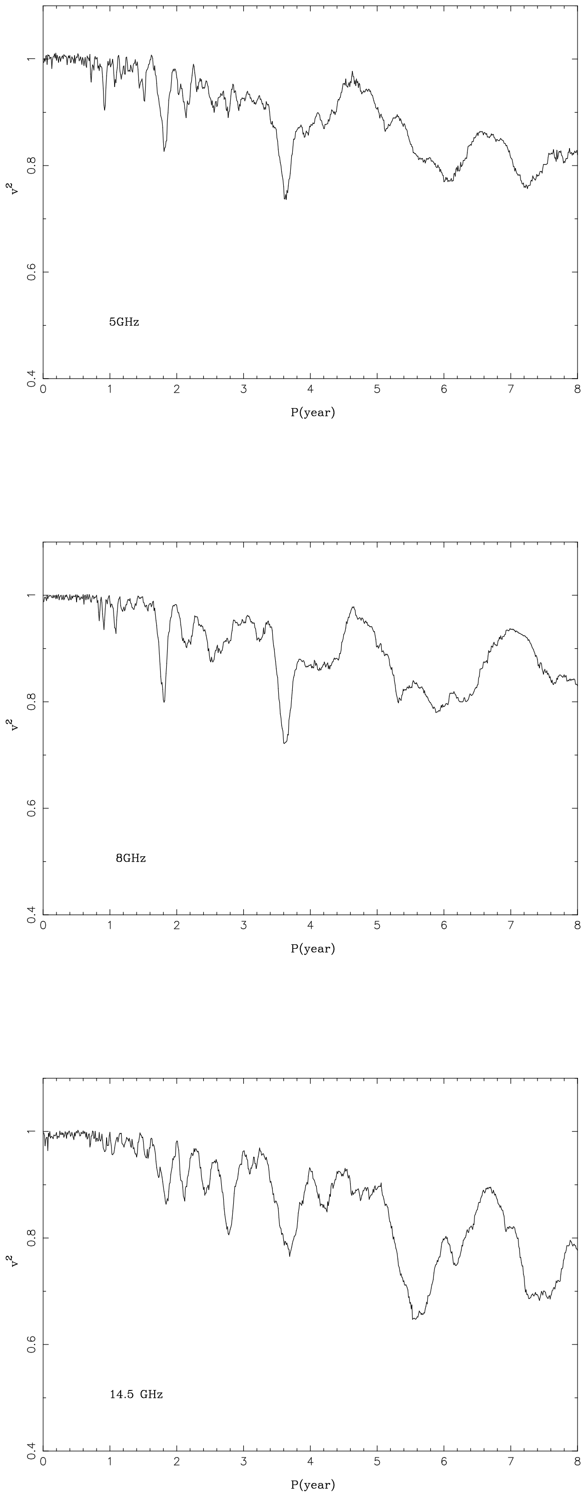


*Figure 5*. Variation of variance with time. (a) $V^2$ - P at 5 GHz; (b) $V^2$ - P at 8 GHz; (c) $V^2$ - P at 14.5 GHz

are listed in Table IV, which is well consistent with the fitting result of the jet positional angles.

Table IV. periods in three different frequencies

| freq.(GHz) | period1(yr) | period2(yr) |
|---|---|---|
| 5 | $1.81 \pm 0.04$ | $3.64 \pm 0.08$ |
| 8 | $1.81 \pm 0.06$ | $3.61 \pm 0.08$ |
| 14.5 | $1.79 \pm 0.07$ | $3.64 \pm 0.13$ |

Chu et al. (1996) suggest that, the shorter periodic variation of the flux density might be the timescale of the jet outbursts, while Zhang et al. (1997) suggest that the longer periodic variation might be due to the precession of its central engine. Both of these two periodic variations are embodied in the variation of the flux density with time, which implies that the central engine may be indeed undergoing precession with a period of $\sim$ 3.6 years. We consider that the longer periodic variation of the flux densities with time shown in Figure 4 might be due to the following reasons: with the rotation of the jet, the angle between the line of sight and direction of the jet varies correspondingly; the amplifying effect, i.e., the beaming effect in the jet varies correspondingly; and the variation of the jet itself will lead to asymmetrical variation of the flux densities between any two circles and weaken the periodicity of the flux density variation. It is the synthetic action of both the rotation and outburst of the jet that forms the relationship between the flux densities and time (see Figure 4).

### 3.3. Superluminal motion and the mass of binary black hole system

Therefore, in order to further investigate the process of evolution, it is necessary to do continuously high resolution observations with an interval of months. To avoid the absorption of $\gamma$ photons by X-ray photons, Madejski et al. (1996) get $\delta > 3.1$ (where $\delta = \Gamma^{-1}(1-\beta cos\theta)^{-1}$, $\theta$ is the angle between the line of sight and the direction of the jet). By comparing the predicted and the observed self-Compton flux, one can derive $\delta$ in the case of a moving sphere (Ghisellini et al. 1993)

$$\delta = f(\alpha)F_c\left[\frac{ln(\nu_b/\nu_c)}{F_x\theta_d^{6+4\alpha}\nu_x^{\alpha}\nu_c^{5+3\alpha}}\right]^{1/(4+2\alpha)}(1+z) \qquad (1)$$

where $F_c$ and $F_x$ are the radio flux density and X-ray flux density in Jy , $\nu_x$ is in keV, $\nu_c$ is the frequency of the observation in GHz, $\theta_d$ is in mas, $\nu_b$ is the synchrotron high frequency cutoff (assumed to be $10^{14}$ GHz), and $f(\alpha) = 0.08\alpha + 0.14$ (here $\alpha = 0.75$ is assumed). A value of $\delta \sim 6.5$ may be obtained when $F_c$, $F_x$, $\nu_c$ and $\theta_d$ are taken to be 1.75 Jy, 0.17 $\mu Jy$, 5.0 GHz and 0.5 mas (Ghisellini et al. 1993). Chu et al. (1996) obtained that the maximum apparent expand velocity is up to $(27\pm6)c$. If so, AO 0235+164 is the source of maximum expand velocity among all superluminal sources.

The maximum value of the angle $\theta_{max}$ between the original jet direction and the line of sight can be obtained by the following expression:

$$\cos\theta_{max} = \frac{\beta_{app}^2 - 1}{\beta_{app}^2 + 1} \tag{2}$$

The resultant $\theta_{max}$ is equal to $5.45°$ when we take the apparent velocity of $21c$ (Chu et al. 1996). Now, we can use the model of massive binary black holes (Kaastra & Roos 1992) to estimate the mass of the central engine. In the special case that the jet and the orbital angular momentum are aligned, the orbital speed can be obtained by:

$$v_{ob} = c\beta \tan\psi \sin\theta \tag{3}$$

where $c\beta$ is the speed of the jet, $\theta$ is the angle between the jet and the line of sight, $\psi$ is the apparent half-opening angle of the jet cone. Here, we take $\psi$ of $19.07°$ from the average of six epochs (Zhang et al. 1997), and $\theta$ is taken to be the value yielding the maximum orbital velocity, i.e. $\theta = \min(\theta_{max}, \pi/2)$, with $\theta_{max}$ given by Eq.(2). With known period and orbital velocity, the minimum total mass of the binary system is equal to $1.46 \times 10^8 M_\odot$, which follows from Kepler's third law.

## 4. Conclusion

From our discussions in this paper AO 0235+164 shows a periodic variation of $\sim 3.6$ year both in the variations of the jet positional angle and the flux densities with time. This implies that the central engine may well be undergoing precession. With the binary black hole models, we get the minimum mass of the binary system of $1.46 \times 10^8 M_\odot$.

Because of the rapid variation of its flux density and radio structure, the present VLBI epochs on this source are not sufficiently close in time to make it possible to distinguish between these models. The acquisition of the apparent motion involves uncertainties, and the periodicity of the variation of the jet positional angle has yet to be further identified.

Therefore, monthly and continuous VLBI observations with global arrays are necessary in order to track down the structural variations and identify components between epochs so that the apparent velocity and the mass of its central engine can be confirmed.

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