Dual-Frequency VSOP Observations of AO 0235+164

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(Received ; accepted )

Abstract

AO 0235+164 is a very compact, flat spectrum radio source identified as a BL Lac object at a redshift of \( z = 0.94 \). It is one of the most violently variable extragalactic objects at both optical and radio wavelengths. The radio structure of the source revealed by various ground-based VLBI observations is dominated by a nearly unresolved compact component at almost all available frequencies.

Dual-frequency space VLBI observations of AO 0235+164 were made with the VSOP mission in January-February 1999. The array of the Japanese HALCA satellite and co-observing ground radio telescopes in Australia, Japan, China and South Africa allowed us to study AO 0235+164 with an unprecedented angular resolution at frequencies of 1.6 and 5 GHz. We report on the sub-milliarcsecond structural properties of the source. The 5-GHz observations led to an estimate of \( T_B > 5.8 \times 10^{13} \) K for the rest-frame brightness temperature of the core, which is the highest value measured with VSOP to date.

Key words: Galaxies: active — Radio continuum: galaxies — Radio sources: variable — BL Lacertae objects: individual (AO 0235+164) — Techniques: interferometric

1. Introduction

The Arecibo Occultation source AO 0235+164 is a well known object extensively studied at nearly all wavelengths. It was identified as a BL Lac object by Spinrad and Smith (1975) based on its almost featureless optical spectrum. Its emission line redshift of \( z = 0.940 \) was first measured by Cohen et al. (1987). Two other absorption redshift systems were detected in the same direction at \( z = 0.851 \) and \( z = 0.524 \). The latter was detected also in emission. There are a number of foreground galaxies within a few arcseconds of AO 0235+164 at the latter redshift, indicating the presence of a group or cluster of star-forming galaxies. Extensive optical studies of the object AO 0235+164 and the surrounding field, both imaging and spectroscopy, are presented in Nilsson et al. (1996), Burbidge et al. (1996) and references therein.

The source is highly variable in the radio (O’Dell et al. 1988; Romero et al. 1997), near-infrared (Takalo et al. 1992), optical (Rabbette et al. 1996) and X-ray (Madejski et al. 1996) regimes of the electromagnetic spectrum. It is detected in gamma-rays by the EGRET on the Compton Gamma-Ray Observatory (von Montigny et al. 1995), with indication of variability during the 1-year observing period. The presence of a group of foreground galaxies led Stickel, Fried & Kühr (1988) to suggest that the dramatic flux density variations, correlated at optical and radio wavelengths, could be explained in terms of gravitational microlensing. Abraham et al. (1993) performed deep imaging of AO 0235+164. Based on the observation and modelling its Mg\( \text{II} \) absorber, they concluded that strong microlensing of AO 0235+164 by individual stars in the intervening galaxy is unlikely. Saust (1992) came to a similar conclusion using emission line variability measurements. It appears that variability is intrinsic to the source and may be best explained by the relativistic beaming model.

Flux density variations across a factor–of–50 range...
Table 1. Imaging VLBI observations of AO 0235+164 from the literature.

| ν (GHz) | Epoch (year) | $S_0^a$ (Jy) | $S_b^b$ (Jy) | $\text{size}^c$ (mas × mas) | $T_B^d$ (10^{11} K) | Array$^e$ | Extension PA | Reference$^f$ |
|---------|--------------|--------------|--------------|------------------|-------------------|----------|--------------|--------------|
| 0.327   | 1986.25      | 0.88         | 0.52         | 19 × 13          | 0.5               | global   | 22$^g$       | AG95         |
| 1.6     | 1999.08      | 1.44         | 1.44         | 0.85 × 0.60      | 18                | SVLBI    | no           | this paper   |
| 2.3     | 1981.89      | 1.2          | 0.8          |                  |                   | global   | 35$^g$       | CU83         |
| 2.3     | 1996.31      | 0.67$^g$     | 7.55 × 3.75  | 0.1              | VLBA E-NE        | USNO     |              |              |
| 2.3     | 1997.03      | 0.41$^g$     | 7.03 × 3.54  | 0.08             | VLBA E-NE        | USNO     |              |              |
| 5       | 1978.9       | 1.89         | 1.89         | 3.5 × 3.5        | 0.8              | global   | 25$^g$       | CB96         |
| 5       | 1979.2       | 3.36         | 3.11         | 2.55 × 1.48      | 0.8              | global   | 14$^g$       | CB96         |
| 5       | 1980.8       | 2.26         | 2.18         | 0.42 × 0.19      | 0.8              | global   |              | CB96         |
| 5       | 1981.9       | 1.78         | 1.72         | 0.31 × 0.31      | 1.7              | global   | 47$^g$       | CB96         |
| 5       | 1981.92      | 2.14         |              |                  |                   | US       | no           | GC89         |
| 5       | 1982.93      | 1.68         |              |                  |                   | US       | no           | GC89         |
| 5       | 1983.5       | 2.27         | 1.81         | < 0.1 × < 0.1    | > 172             | global   | −163$^g$     | CB96         |
| 5       | 1986.45      | 1.57         |              |                  |                   | global   | no           | GC89         |
| 5       | 1987.41      | 2.87         | 2.87         | 0.53 × 0.53      | 10                | global   | no           | GC92         |
| 5       | 1992.9       | 4.57         | 4.45         | 0.4 × 0.2        | 53                | global   | 58$^g$       | SW97         |
| 5       | 1996.42      | 0.43         | 0.43         | < 0.7 × 0.6      | > 10              | VLBA     | no           | FF00         |
| 5       | 1997.13      | 0.30         | 0.29         | 0.79 × 0.59      | 0.5               | EVN      | 47$^g$ and −45$^g$ | CZ99       |
| 5       | 1999.08      | 1.23         | 0.92         | < 0.05 × < 0.03  | > 580             | SVLBI    | −57$^g$      | this paper   |
| 8.4     | 1990.47      | 2.67         | 2.67         | 0.1 × 0.1        | 90                | global   | no           | GC96         |
| 8.4     | 1996.31      | 0.29$^g$     | 2.07 × 1.03  | 0.05             | VLBA E and E-NE? | USNO     |              |              |
| 8.4     | 1997.03      | 0.21$^g$     | 1.9 × 0.97   | 0.04             | VLBA               | USNO     |              |              |
| 8.4     | 1999.03      | 1.57         | 0.31 × 0.26  | 6.5              | VLBA               | no       | V00          |             |
| 15      | 1995.57      | 0.67$^g$     | 1.2 × 0.6    | 0.1              | VLBA               | no       | KV98         |             |
| 15      | 1995.96      | 0.31$^g$     | 1.2 × 0.6    | 0.05             | VLBA               | no       | KV98         |             |
| 15      | 1996.31      | 0.36$^g$     | 1.07 × 0.57  | 0.06             | VLBA               | no?      | USNO         |             |
| 15      | 1997.67      | 1.41$^g$     | 1.2 × 0.6    | 0.2              | VLBA               | no       | KV98         |             |
| 22      | 1982.9       | 1.38         | 1.30         | 0.1 × 0.1        | 6                 | global   | 7$^g$        | JB84         |
| 22      | 1993.9 – 1996.7 (3) | | | | | VLBA | no | XW98 |
| 22      | 1999.03      | 1.04         | 1.04         | 0.20 × 0.08      | 3.2               | VLBA     | no           | V00          |
| 43      | 1993.9 – 1996.7 (3) | | | | | VLBA | no | XW98 |

[a] flux density is the sum of the fitted model component flux densities cited in the VLBI reference (where available)
[b] flux density of the core
[c] Gaussian model size of the core (FWHM)
[d] lower limit for the core brightness temperature estimated from fitted model flux densities and angular sizes
[e] EVN=European VLBI Network; SVLBI=space VLBI; VLBA=Very Long Baseline Array
[f] AG95=Altschuler et al. 1995; BE81=Bäath et al. 1981; CB96=Chu et al. 1996; CU83=Cohen et al. 1983; CZ99=Chen, Zhang & Sjouwerman 1999; FF00=Fomalont et al. 2000; GC89=Gabuzda et al. 1989; GC92=Gabuzda et al. 1992; GC96=Gabuzda & Cawthorne 1996; JB84=Jones et al. 1984; KV98=Kellermann et al. 1998; SW97=Shen et al. 1997; USNO=US Naval Observatory [http://maia.usno.navy.mil/rorf/rrfid.html]; V00=T. Venturi et al. 2000, in preparation; XW98=Xu, Wehrle & Marscher 1998
[g] peak brightness and restoring beam size in the VLBI image were used to substitute $S$ and size, to obtain a rough estimate of $T_B$, assuming that the core is unresolved

In radio frequencies during a 5-year monitoring interval were found to be correlated, suggesting that they are intrinsic to the object. The radio variability can qualitatively be understood in terms of adiabatically evolving structures in a relativistic jet (O’Dell et al. 1988). However, Romero et al. (1997) favor refractive scintillation as the simplest explanation of intraday radio variability observed in AO 0235+164. Most recently, Kraus
et al. (1999) analysed contemporaneous radio and optical monitoring data taken in October 1992 over a period of about a month. They discuss several models to explain the observations, including relativistic shock-fronts, precessing beams, free-free absorption by the foreground medium, interstellar scattering and gravitational microlensing. Since apparently none of the models investigated accounts for the observed variations alone, Kraus et al. suggest that the variability is caused by a superposition of intrinsic and propagation effects. They note that all explanations imply a very small intrinsic source size and require a Doppler factor substantially larger than usual (up to 100) to be consistent with the inverse Compton brightness temperature limit of \( \sim 10^{12} \) K (Kellermann & Pauliny-Toth, 1969).

A large number of VLBI images of AO 0235+164 have been produced over a wide range of observing wavelengths (from millimeters to meters). We have collected a long, albeit certainly incomplete, list of references in Table 1. A large fraction of the VLBI images do not show any extended structure except from the very compact core, regardless of the different angular resolution and the actual total flux density at the observing time (e.g. Gabuzda et al. 1989, 1992, 1996; Xu, Wehrle & Marscher 1998). On the other hand, several authors report faint extensions at a variety of position angles (PA), but mainly between the north and east (e.g. Jones et al. 1984; Chu et al. 1996; Shen et al. 1997). Although the components found by Chu et al. (1996) appear to move too fast to be identifiable between the subsequent epochs, these authors, based on the assumption that the components observed are the results of outbursts at earlier epochs, come to an estimate of the Doppler boosting of the order 10^9.

Several non-imaging VLBI surveys, e.g. Preston et al. (1985) at 2.3 GHz, Morabito et al. (1986) at 2.3 and 8.4 GHz and Moellenbrock et al. (1996) at 22 GHz, also found AO 0235+164 to be extremely compact. The source is often used as a fringe-finder and calibrator for VLBI experiments.

2. VSOP space VLBI observations, calibration and data reduction

AO 0235+164 was observed in the VLBI Space Observatory Programme (VSOP, Hirabayashi et al. 1998) at 1.6 GHz on 31 January 1999 with the HALCA satellite via the tracking stations at Tidbinbilla (Australia), Goldstone (USA), Usuda (Japan) and Robledo (Spain). The participating ground telescopes were the Australia Telescope Compact Array (ATCA), Sheshan (China), Hartebeesthoek (South Africa) and Noto (Italy). The 5-GHz VSOP observation took place on 1 February 1999. HALCA was tracked from Tidbinbilla. The three co-observing ground radio telescopes were ATCA, Sheshan and Usuda. The data in both experiments were recorded in left circular polarization in S2 format (Wietfeldt et al. 1996) with 32 MHz bandwidth. Correlation was performed at the Dominion Radio Astrophysical Observatory in Penticton (Canada) (Carlson et al. 1999).

Data calibration and fringe-fitting with 5-min solution interval were done with the NRAO AIPS package (version 15OCT98; e.g. Cotton 1995, Diamond 1995). Time averaging, editing, self-calibration and imaging were done using the DIFMAP program (version 2.3c; Shepherd, Pearson & Taylor 1994).

Strong fringes were found in the 5-GHz experiment for all available antennas and time ranges. Measured system temperatures were available at Sheshan and Usuda for initial amplitude calibration. Nominal values were used for HALCA and ATCA. The calibrator source 0420−014 was used to adjust the antenna gains of the ground telescopes. The total flux density of 0420−014 is being monitored at the University of Michigan Radio Astronomy Observatory (UMRAO, http://www.astro.lsa.umich.edu/obs/radiotel/umrao.html). The source was observed in the 5-GHz VSOP-VLBA Pre-launch Survey (VLBAlps, June 1996, Fomalont et al. 2000). Based on the similar 5-GHz total flux densities at the epochs of the VLBAlps and our VSOP observation, and assuming that the source structure found in the VLBAlps has not changed considerably since 1996, the ground telescope gains had to be corrected by factors of 1.3, 1.5 and 3.3 for ATCA, Sheshan and Usuda, respectively. The unusually large correction factor for Usuda is explained by the fact that the quantizer threshold was set incorrectly for this telescope, as noted at the correlator. Initial HALCA amplitude calibration could not be checked but it is known to be stable (Moellenbrock et al. 2000).

The \((u,v)\) coverage for the 5-GHz experiment is shown in Fig. 1. Fig. 2 shows the visibility amplitudes and phases as a function of projected baseline length up to 420 million wavelengths (\(\lambda_{\text{A}}\)), along with the curves representing the final clean-component model. The uniformly weighted image is shown in Fig. 3.

In the case of the 1.6-GHz experiment, the initial amplitude calibration was based on the measured system temperatures and gain curves for Hartebeesthoek, Noto and Sheshan. Nominal system temperatures were used for ATCA and HALCA. Fringe-fitting resulted in strong fringes for all available baselines except those to Sheshan, where no fringes were found. This, and the fact that the source was observed during a very limited common time range at the remaining antennas, made the traditional hybrid mapping of AO 0235+164 impossible at this observing frequency. Model fitting to the visibility data in DIFMAP resulted in an elliptical Gaussian component with flux density of 1.44 Jy, angular size of 0.85 mas × 0.60 mas (FWHM) and major axis position...
Fig. 1. The \((u, v)\) coverage of the 5-GHz space VLBI experiment. Participating ground antennas are ATCA, Sheshan and Usuda. Projected baselines to HALCA extend up to 420 M\(\lambda\).

Fig. 2. Self-calibrated visibility amplitude (Jy) and phase (degrees) vs. projected baseline length for AO 0235+164 at 5 GHz. Solid lines represent the clean component model used for restoring the image in Fig. 3.

Fig. 3. 5-GHz space VLBI image of AO 0235+164. Restoring beam is 0.49\(\times\)0.26 milliarcsecond at PA=62\(^\circ\), contour levels are at \(-1, 1, 2, 5, 10, 25, 50, 99\)% of the peak brightness of 910 mJy/beam.

Fig. 4. Calibrated visibility amplitude (Jy) and phase (degrees) vs. projected baseline length for AO 0235+164 at 1.6 GHz. Reliable amplitude self-calibration could not be made due to the lack of four useful antennas in the array for most of the observing time.

angle of \(-14^\circ\). Fig. 4 shows the visibility amplitudes and phases vs. projected baseline length. The data were edited and averaged over 30 s intervals in DIFMAP. The ground telescope antenna gains were again adjusted using the total flux density data taken simultaneously and assuming that the source is unresolved on the shortest baselines. The gain correction factors were 1.4, 1.4 and 1.8 for Noto, Hartebeesthoek and ATCA, respectively.

3. Discussion
3.1. Sub-milliarcsecond structure

At 5 GHz, the structure of AO 0235+164 on sub-milliarcsecond scale is dominated by a compact component, with a weak extension to approximately the northwest (Fig. 3). Its position angle is not quite the same as that found in many VLBI images published earlier (see Table 1), including the 22-GHz ground VLBI image of Jones et al. (1984) which has almost exactly the same angular resolution. Note that earlier ground-only VLBI imaging observations led to controversial results on the existence and position angle of the extended features, which most likely indicates rapid structural variations. However, the existence of such an extension must be treated with some caution because of the relatively sparse \((u, v)\) coverage in our space VLBI observation. The visibility data of AO 0235+164 are consistent with a central point-source and an elliptical Gaussian component, according to model fitting in DIFMAP. The model parameters are listed in Table 2. Indeed, the source is remarkably compact: the correlated flux density ratio between the longest and shortest projected baselines is 3:5 (Fig. 2).

3.2. Source spectrum

At the time of our observations, the total flux density of AO 0235+164 was declining according to the data from the UMRAO long-term monitoring program at three different radio frequencies (Aller et al. 1999). The total flux density data at 4.8 GHz are shown in Fig. 5, indicating the epoch of our observations. The quasi-single epoch source spectrum (Fig. 6) is constructed from measurements at UMRAO and the Arecibo Observatory on 30 January 1999. The flux density over a range spanning an order of magnitude in frequency (from 1.175 to 14.5 GHz) is roughly constant. It can be well described with a power-law spectral index, \(\alpha = -0.02 \pm 0.03 \) \((S \sim \nu^\alpha)\). Although there are no measurements available at lower frequencies, a spectral turnover at \(\sim 2\) GHz may be suspected.

It should be noted that the relatively large ground radio telescope gain correction factors used for amplitude calibration of our space VLBI data lead to correlated flux densities of \(\sim 1.5\) Jy on the shortest baselines. This is in agreement with the contemporaneously measured total flux densities and the well-known compact nature of AO 0235+164 which makes this source a widely used VLBI fringe-finder and calibrator.

3.3. Brightness temperature

A lower limit for the rest-frame brightness temperature of the source can be estimated as

\[
T_B[K] = 1.22 \times 10^{12} \frac{S}{\theta_{maj}\theta_{min}} \frac{1 + z}{\nu^2},
\]

(1)
Table 2. Fitted model parameters of the source components at 5 GHz. Angular size upper limits and uncertainties are calculated from the image parameters, following Fomalont et al. (2000).

| Component | S (mJy) | r (mas) | θ (°) | a (mas) | b (mas) | Φ (°) |
|-----------|---------|---------|-------|---------|---------|-------|
| Core      | 915     | 0.04    | 127   | < 0.05  | < 0.03  | −     |
| A         | 319     | 0.21    | −57   | 0.60 ± 0.02 | 0.20 ± 0.02 | 37 |

S: flux density, r: separation from the field center, θ: position angle, a: major axis, b: minor axis, Φ: position angle of the major axis; position angles are measured from north through east.

where $S$ is the component flux density in Jy, $\theta_{maj}$ and $\theta_{min}$ are the major and minor axes, respectively, in mas (assuming optically thick Gaussian brightness distribution), $\nu$ is the observing frequency in GHz and $z$ is the redshift. For the core of AO 0235+164, at the redshift of $z = 0.94$, we obtain $T_B > 5.8 \times 10^{13}$ K using the source model from the 5-GHz experiment (Table 2). This is a direct evidence for a brightness temperature exceeding the inverse Compton limit and can be interpreted, in particular, as a result of relativistic motion in the source.

Earlier brightness temperature estimates for AO 0235+164 were based on e.g. 22-GHz VLBI survey data ($T_B > 2 \times 10^{12}$ K, Moellenbrock et al. 1996), 5-GHz ground-based VLBI imaging ($T_B = 5.3 \times 10^{12}$ K, Shen et al. 1997) and variability ($T_B = 7 \times 10^{17}$ K for $\lambda = 20$ cm, Kraus et al. 1999). We have made an attempt to compile a list of brightness temperature lower limit estimates using the VLBI imaging experiments cited in Table 1, according to Eq. 1. Calculated $T_B$ values are based on fitted Gaussian core model component flux densities and angular sizes given in the references where available. The brightness temperature was estimated using image parameters (peak brightness and restoring beam size, assuming that the source is not resolved) where only images were available. The values as a function of time are plotted in Fig. 7 using the same time scale as for the total flux density monitoring data (Fig. 5). The estimates of $T_B$ are lower limits, the time sampling is quite sparse, and the values were calculated from VLBI experiments made at different frequencies, and thus with different sensitivities, to determine the brightness temperature. Nevertheless, there is an indication of a correlation between the long term behaviour of $T_B$ and measured total flux densities (Fig. 8). The correlation cannot arise from the dependence of $T_B$ on $S$ alone, since source size is also highly variable (see Table 1) and $T_B$ varies in a range spanning four orders of magnitude (Fig. 7). This possible correlation is qualitatively consistent with the picture that each flux density outburst marks the birth of a new, relativistic component which later fades away and the angle between the direction of motion and the line of sight increases (Chu et al. 1996). As the jet direction in BL Lac objects is thought to be oriented very close to the line of sight, this change causes significant decrease in the Doppler boosting factor.

4. Conclusions

Our 5-GHz VSOP space VLBI experiment shows the BL Lac object AO 0235+164 to be very compact on submilliarcsecond angular scales. The rest-frame brightness temperatures estimated from the source angular size and observed flux density clearly exceed $10^{12}$ K which can be explained by strong Doppler boosting. The brightness temperature $T_B > 5.8 \times 10^{13}$ K obtained from the 5-GHz data is the highest value found with VSOP observations to date (cf. Lovell et al. 2000). This implies a Doppler
factor of $\sim 100$, in good agreement with the results of several recent studies (e.g. Kraus et al. 1999, Fujisawa et al. 1999), although the source total flux density was relatively low at the time of our observations.

There is an indication of an extended component to N-NW, at the position angle about $90^\circ$ away from what is sometimes seen in ground VLBI images. Due to the possibly very small jet angle with respect to the line of sight (e.g. $\phi \leq 0.35$ is estimated by Fujisawa et al. 1999), small deviations in the intrinsic direction of the jet ejection could cause large changes in the observed jet position angle.

Further high resolution VLBI monitoring observations, either with space VLBI and/or ground-based VLBI at higher frequencies ($\nu \geq 15$ GHz), would be needed to identify possible components ejected after major outbursts occurring every 3–5 years.

We gratefully acknowledge the VSOP Project, which is led by the Institute of Space and Astronautical Science (Japan) in cooperation with many organizations and radio telescopes around the world. The Arecibo Observatory is operated by Cornell University under cooperative agreement with the National Science Foundation. This research has made use of data from the University of Michigan Radio Astronomy Observatory which is supported by funds from the University of Michigan and the National Science Foundation. This research has made use of the United States Naval Observatory (USNO) Radio Reference Frame Image Database. SF acknowledges financial support received from the Hungarian Space Office, the Netherlands Organization for Scientific Research and the Hungarian Scientific Research Fund (grant no. N31721 & T031723). We thank Tiziana Venturi for providing us with their 8.4 and 22-GHz VLBA imaging results prior to publication.

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