Boletim da Sociedade Astronômica Brasileira, **32**, no. 1, 58-59

Kinematics of the relativistic jet of BL Lac object AO 0235+164

Flávio Benevenuto da Silva Junior[1] & Anderson Caproni[2]

[1] Núcleo de Astrofísica, Universidade Cruzeiro do Sul, R. Galvão Bueno 868, Liberdade, 01506-000, São Paulo, SP, Brazil e-mail: flavio.ben@outlook.com

[2] Núcleo de Astrofísica, Universidade Cruzeiro do Sul/Universidade Cidade de São Paulo, R. Galvão Bueno 868, Liberdade, 01506-000, São Paulo, SP, Brazil e-mail: anderson.caproni@cruzeirodosul.edu.br

Abstract. Radio interferometric images of blazar AO 0235+164 show the existence of a stationary core, and a compact jet composed of multiple components. In this work, we determine the structural characteristics of these jet components (core-component distance, position angle, flux density, etc.) at the frequencies of 15 and 43 GHz using our statistical method for global optimization Cross-Entropy. The analyzed images were extracted from public databases (MOJAVE Project; BU Blazar Group), totalizing 41 images at 15 GHz and 126 at 43 GHz. Using criteria such as the value of the CE merit function, and mean residuals, we determined the optimum number of components in each epoch analyzed in this work. The temporal evolution of the spatial coordinates of the jet components was used to determine their speeds and ejection epochs. To date, more than 20 components have been identified in the jet of AO 0235+164, with apparent speeds roughly between 2c and 40c, and distributed across all four quadrants in the plane of the sky. Based on these values, the value of the Lorentz factor and the angle of orientation of the jet in relation to the line of sight are estimated in this work.

Resumo. Imagens interferométricas de rádio do blazar AO 0235+164 mostram a existência de um núcleo estacionario e um jato compacto, composto por multiplas componentes. Neste trabalho, nós determinamos as características estruturais destas componentes (por exemplo distância componente-núcleo, angulo de posição, densidade de fluxo, etc) nas frequências de 15 e 43 GHz utilizando o método estatístico de otmização global Cross-Entropy. As imagens analisadas foram extraídas de base de dados públicas (MOJAVE Project; BU Blazar Group), totalizando 41 imagens em 15 GHz e 126 imagens em 43 GHz. Usando como critério os valores da função de mérito CE e residuo médio, nós determinamos o número ótimo de componentes em cada época analizada neste trabalho. A evolução temporal das coordenadas espaciais das componentes do jato foram utilizadas para determinar as velocidades e épocas de ejeção das componentes. Até o momento, mais de 20 componentes foram identificadas no jato de AO 0235+164, com velocidades aparentes entre 2c à 40 e distríbuidas em todos o quadrantes do plano do céu. Com base nestes valores, o valor do fator de Lorentz e do ângulo de orientação do jato em relação a linha de visada foram estimados neste trabalho.

Keywords. methods: data analysis – techniques: interferometric – galaxies: active – galaxies: jets – BL Lacertae objects: individual: AO 0235+164 – radio continuum: galaxies

1. Introduction

Radio interferometric images of the BL Lac object AO 0235+164 (z = 0.9399 e.g, Cohen et al. 1987) show the existence of a stationary compact core, and a compact jet composed of multiple components moving at extreme superluminal velocities (e.g, Lister et al. 2009a,b; Figure 1).

AO 0235+164 exhibits violent variability across the electromagnetic spectrum (including gamma-rays) on time-scales from hours to years (e.g., Ackermann et al. 2012).

2. Results

We analyzed 126 interferometer maps at 43 GHz obtained from the Boston University blazar group data archive and 41 interferometric maps at 15 GHz obtained from the MOJAVE Project archive. The structural parameters of the elliptical Gaussian components were determined via Cross-Entropy (CE) global optimization technique (e.g, Rubinstein 1997; Caproni, Monteiro, Abrahan 2009; Caproni et al. 2014). We identified 25 jet components (C1-C25) that recede ballistically from the core with differents superluminal apparent speeds (Figure 2) and sky position angles (Figure 3).

Ejections of the jet components coincide with flares detected at gamma-rays and by OVRO telescope, as well the increase of core flux density (Figure 4). The minimum value for the Lorentz factor was obtained from the maximum apparent speed, which in our analysis corresponds to the C2 component: $\gamma_{min} \geq (39.2 \pm 11.8)$, and the maximum jet viewing angle comes from the minumum apparent speed among jet components and taking $\beta \rightarrow 1$ (β is bulk jet speed): $\theta_{max} \leq (42.1^o \pm 19.8^o)$.

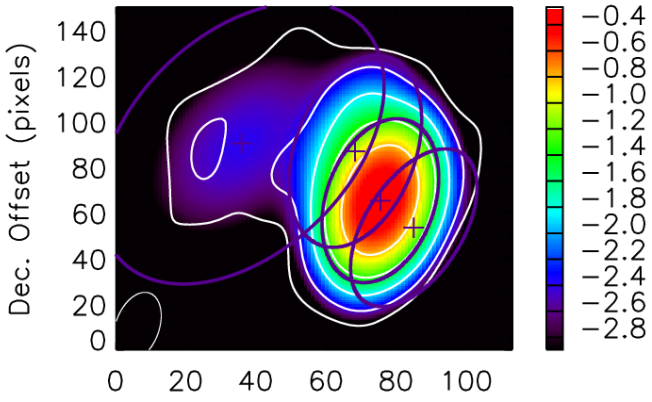

Figure 1. Interferometric image of the AO 0235 + 164 jet (logarithmic scale in Jy/beam) obtained on August 26, 2018 with four CE model-fitted components.

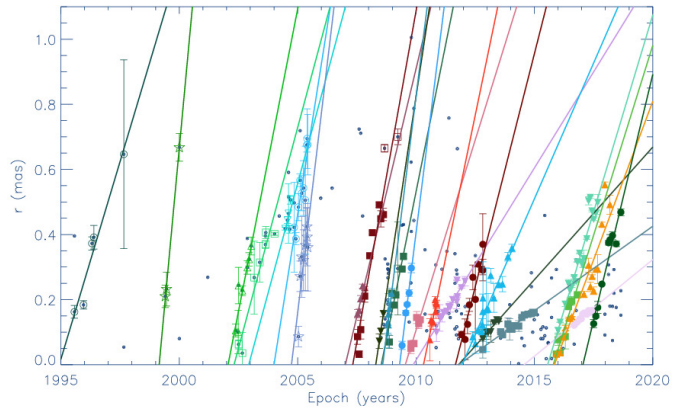

Figure 2. Component-core temporal evolution of the 25 components of the AO 0235 + 164 jet identified in this work. The open symbols from 1995 to 2005 represent the distances traveled by the 7 components identified for the jet at a frequency of 15 GHz, namely. The symbols solids present on the straights between 2007 and 2020 represent the distances identical components at 43 GHz. The straight lines at this figure show the result of the linear regression, for each individual component. Small points show unidentified jet components in this work.

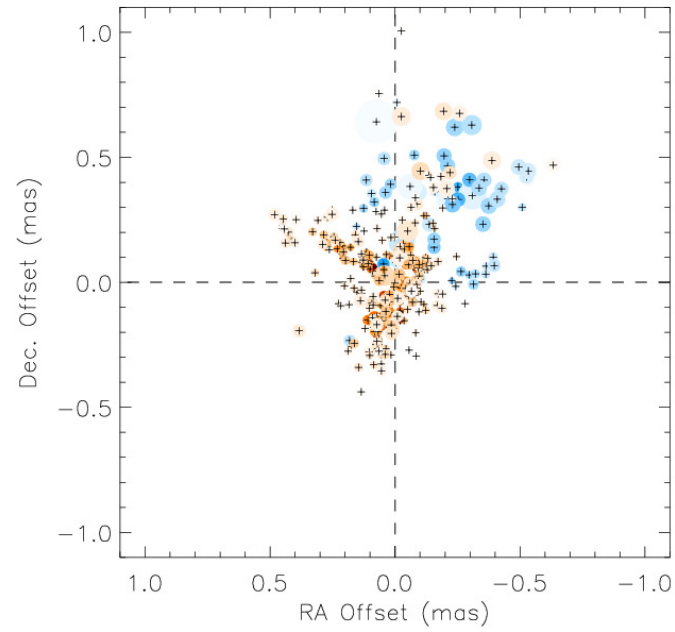

Figure 3. Schematic representation illustrating the spatial distribution of the coordinates of ascent as well as the declination of the jet components identified via the CE method throughout the ages studied in this work. The circles in blue correspond to the components identified at 15 GHz. Orange circles correspond to components identified at 43 GHz. The dashed lines mark the core position.

3. Conclusions

We were able to identify 25 components that have different apparent speeds, ranging from about 2c to 40c, and scattered in all quadrants on the sky plane. The minimum value for the Lorentz factor and the maximum jet viewing angle also were estimated in this work: $\gamma_{min} \geq (39.2 \pm 11.8)$ and $\theta_{max} \leq (42.1^o \pm 19.8^o)$.

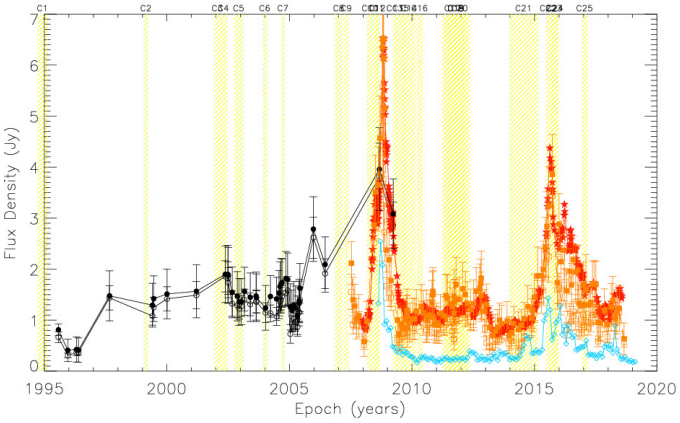

Figure 4. Flux density behavior of AO 0235 + 164 between 1995 and 2019. The solid and open black circles represent, respectively, the 15-GHz flux density behavior of the total (core+components) and the core. The solid and open squares show, respectively, the 43-GHz flux density behavior of the total (core+componentes) and the core. The red stars represent the AO light curve AO 0235 + 164 obtained by the OVRO Telescope. Open blue diamonds represent the light curve in gamma rays obtained by the FERMI experiment. The yellow vertical rectangles mark the ejection of the 25 componentes in this work, with their widths representing the respective uncertainties in the ejection epochs.

We also found variations in the position angles of the jet components. Such variations indicate that the jet direction does not remain constant (fixed) over time. A plausible explanation for explaining such dispersion could be the jet precession phenomenon, which will be investigated in a future work.

Acknowledgements. F.B.S.J. thanks the Brazilian agency CAPES for financial support. A.C. thanks the Brazilian agency FAPESP (grants 2017/25651-5 and 2014/11156-4).

This research has made use of data from the MOJAVE database that is maintained by the MOJAVE team (Lister et al. 2009). This study makes use of 43 GHz VLBA data from the VLBA-BU Blazar Monitoring Program (VLBA-BU-BLAZAR; http://www.bu.edu/blazars/VLBAproject.html), funded by NASA through the Fermi Guest Investigator Program. The VLBA is an instrument of the National Radio Astronomy Observatory. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated by Associated Universities, Inc.

References

Ackermann M., et al., 2012, ApJ, 751, 159
Caproni, A., Monteiro, H., Abraham, Z. 2009, MNRAS, 399, 1415
Caproni, A., Tosta e Melo, I., Abraham, Z., Monteiro, H., Roland, J. 2014, MNRAS, 441, 187
Cohen, R. D., Smith, H. E., Junkkarinen, V. T., et al. 1987, ApJ, 318, 577
Lister, M. L. et al. 2009a, AJ, 137, 3718
Lister, M. L., et al. 2009b, AJ, 138, 1874
Lister, M. L. et al. 2018, ApJS, 232, 12
Rubinstein, R. Y. 1997, European Journal of Operational Research, 99, 89