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Kinematic study of the relativistic jets of the blazars AO 0235+164 and PKS 2145+067

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Abstract. Interferometric radio images of the blazars AO 0235+164 and PKS 2145+067 show the existence of a stationary core, and a compact jet composed of multiple components moving with extreme superluminal velocities. In this work, we analyze the structural parameters of these components (e.g, component-core distance, position angle, flux density, etc.) at the frequencies of 15 and 43 GHz using our statistical method of global optimization Cross-Entropy (CE). The analyzed images were extracted from public databases (MOJAVE Project for the data at 15 GHz and Blazar Group BU for the 43 GHz data), totalizing 41 images at 15 GHz and 143 at 43 GHz for AO 0235+164, and 27 images at 15 GHz and 5 at 43 GHz for PKS 2145+067. Using criteria such as the values of the merit function and the mean residuals, the optimum number of jet components was determined for each epoch analyzed in this work. The temporal evolution of the spatial coordinates of the components was used to determine their velocities and ejection times. To date, 35 components have been identified in the AO 0235+164's jet, with apparent speeds between 2c and 40c, and position angles in all quadrants in the sky plane, and 11 components in the case of PKS 2145+067, with apparent velocities between 10c and 18c and position angles between 0.03 and 11.29 degrees. Based on these values, estimates of the Lorentz factor and the viewing angle of these jets are also provided in this work.

Resumo. Imagens interferométricas de rádio dos blazares AO 0235+164 e PKS 2145+067 mostram a existência de um núcleo estacionário, e um jato compacto composto por múltiplas componentes movendo-se com velocidades superluminais extremas. Neste trabalho, analisamos os parâmetros estruturais dessas componentes (por exemplo, distância componente-núcleo, ângulo de posição, densidade de fluxo, etc.) nas frequências de 15 e 43 GHz usando nosso método estatístico de otimização global Cross-Entropy (CE). As imagens analisadas foram extraídas de bancos de dados públicos (Projeto MOJAVE para os dados em 15 GHz e Blazar Group BU para os dados em 43 GHz), totalizando 41 imagens em 15 GHz e 143 em 43 GHz para AO 0235+164, e 27 imagens em 15 GHz e 5 em 43 GHz para PKS 2145+067. Utilizando critérios como os valores da função de mérito e os resíduos médios, o número ótimo de componentes do jato foi determinado para cada época analisada neste trabalho. A evolução temporal das coordenadas espaciais das componentes foi utilizada para determinar suas velocidades e épocas de ejeção. Até o momento, foram identificados 35 componentes no jato do AO 0235+164, com velocidades aparentes entre 2c e 40c, e ângulos de posição em todos os quadrantes do plano do céu, e 11 componentes no caso de PKS 2145+067, com velocidades aparentes entre 10c e 18c e ângulos de posição entre 0,03 e 11,29 graus. Com base nesses valores, estimativas do fator de Lorentz e do ângulo de visão desses jatos também são fornecidas neste trabalho.

Keywords. methods: data analysis – techniques: interferometric – galaxies: active – galaxies: jets – BL Lacertae objects: individual: AO 0235+164 – radio continuum: galaxies - galaxies: jets – quasars: individual: PKS 2145+067 – radio continuum: galaxies.

1. Introduction

1.1. Jets of AO 0235+164 and PKS 2145+067

Radio interferometric images of the Blazar AO 0235+164 (z = 0.94 e.g, Cohen et al. 1987) show the existence of a stationary compact core (the order of 0.8 mas or millisecond of arc e.g, Kutkin et al. 2018) and a compact jet evolving over time. 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).

Located at a redshift z = 0.990 (Steidel and Sargent 1991), this source is classified as a flat spectrum radio quasar (FSRQ; Padovani 1992). Interferometric observations at 5 GHz performed by Wehrle et al. [1992] showed an extended jet (with a position angle of 140 degrees in the sky plane), plus a weak diffuse component at an angular distance of 10 mas from the nucleus, following the same position angle of 140 degrees. Even at higher frequencies (86 and 215 GHz), 2145+067 proves to be a compact source on parsec scales (Greve et al., 1995).

2. Results

For AO 0235+164, we have extended the previous studies analyzing 143 interferometer images 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. Similarly to PKS 2145+067, we have extended the previous studies analyzing 5 interferometer images at 43 GHz obtained from the Boston University blazar group data archive and 27 interferometric maps at 15 GHz obtained from the MOJAVE Project archive.

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).

Jet component motions are compatible with non-accelerated trajectories (Figs. 1 and 2). Jet components in AO 0235+164 are distributed over all quadrants on the plane of the sky, while a south-east distribution is seen in the case of PKS 2145+067 (Fig. 3). Ejection of the jet components coincides fairly with flares seen in the core and gamma-ray light curves (Figs. 4 and 5).

For AO 0235+164, we obtained the minimum value for the Lorentz factor from the maximum apparent speed, (component C2): $\gamma_{min} \geq (39.2 \pm 11.8)$. The maximum jet viewing angle

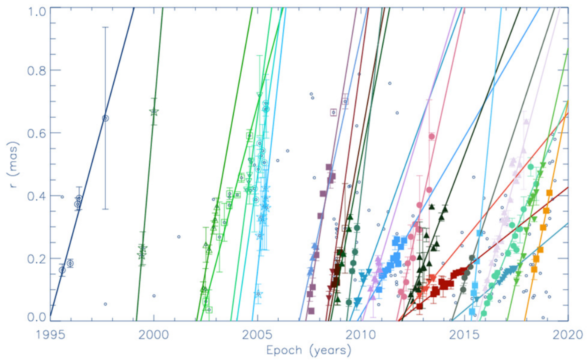

Figure 1. Temporal evolution component-core distance of the jet components of AO 0235+164.

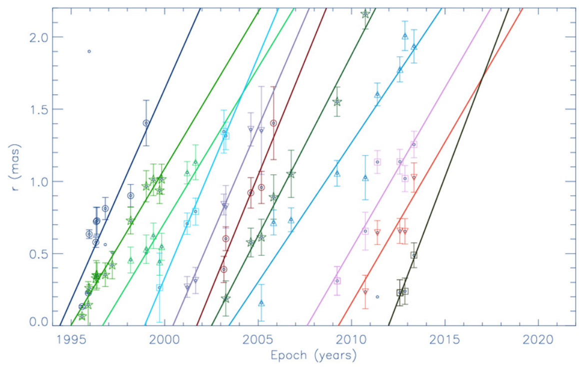

Figure 2. Temporal evolution component-core distance of the jet components of 2145+067.

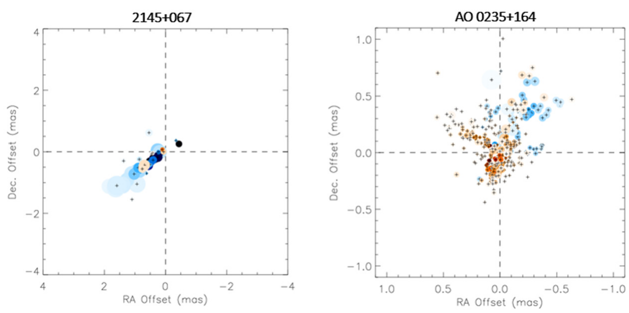

Figure 3. Spatial distribution of identified jet components.

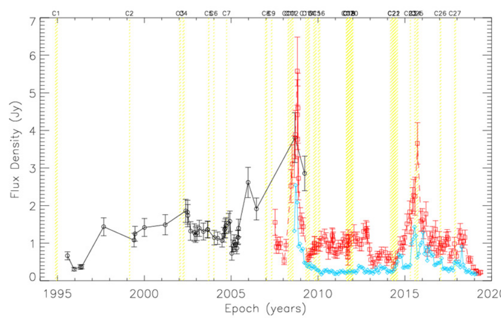

Figure 4. Blazar AO 0235+164 flux density behavior between the 1995 to 2021 epochs.

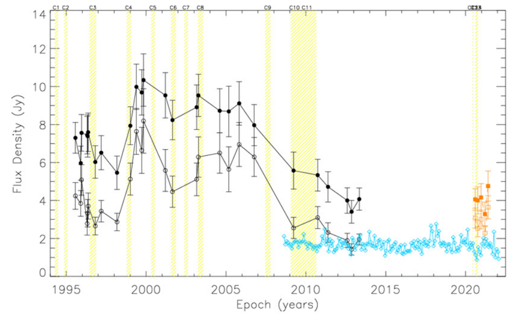

Figure 5. Blazar 2145+067 flux density behavior between the 1995 to 2021 epochs.

comes from the minumum apparent speed among jet components and taking β equals 1 (β is bulk jet speed): $\theta_{max} \leq (42.1° \pm 19.8°)$. In the case of PKS 2145+067 we obtained the minimum value for the Lorentz factor from the maximum apparent speed (component C11): $\gamma_{min} \geq (17.90 \pm 3.20)$. Its maximum jet viewing angle results to $\theta_{max} \leq (11.29° \pm 0.24°)$.

3. Conclusions

We were able to identify 35 parsec-scale jet components in AO 0235+164 that have different apparent speeds, ranging from 2c to 40c, and scattered in all quadrants on the plane of the sky. The minimum value for the Lorentz factor and the maximum jet viewing angle were estimated for this source: $\gamma_{min} \geq (39.2 \pm 11.8)$ and $\theta_{max} \leq (42.1° \pm 19.8°)$. In the case of PKS 2145+067 we were able to identify 11 componentes that have different apparent speeds, ranging from 10c to 18c, and position angles between 0.03 and 11.29 degrees. Its minimum value for the Lorentz factor and the maximum jet viewing angle corresponds to $\gamma_{min} \geq (17.90 \pm 3.20)$ and $\theta_{max} \leq (11.29° \pm 0.24°)$ in agreement with previous estimates. We found variations in the position angles (AO 0235+164) and velocities of the jet components. Such variations indicate that the jet direction does not remain constant (fixed) over time. A possible explanation for explaining such dispersion could be the jet precession phenomenon (e.g., Caproni et al. 2017), which will be explored in a future work.

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