The compact radio structure of the high-redshift blazar J1430+4204 before and after a major outburst

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Abstract. The high-redshift (z = 4.72) blazar J1430+4204 produced an exceptional radio outburst in 2006. We analyzed 15-GHz radio interferometric images obtained with the Very Long Baseline Array (VLBA) before and after the outburst, to search for possible structural changes on milli-arcsecond angular scales and to determine physical parameters of the source.

1. Introduction
Active galactic nuclei (AGNs) are thought to harbor supermassive (up to ∼ 10¹⁰ M☉) black holes. Accretion onto these black holes is responsible for the extreme luminosity of AGNs over the whole electromagnetic spectrum. Part of the infalling matter may be transformed into jets ejected with relativistic speeds. The radio emission in radio-loud AGNs originates from these jets via synchrotron process. If a jet points close to the line of sight toward the observer, its brightness is significantly enhanced. For a review of the unified model of AGNs see Urry & Padovani (1995).

A particular class of AGNs are blazars. They show large variations in brightness from the radio to the gamma-ray regime. They have no emission lines characteristic to other AGNs in the optical spectrum. According to the physical models of AGN (Urry & Padovani 1995), we see at these objects almost exactly in the direction of the jet.

J1430+4204 (B1428+4217) is a blazar with a flat radio spectrum at an extremely high redshift, z = 4.72 (Hook & McMahon 1998). Radio flux density monitoring at 15 GHz revealed a significant brightening of J1430+4204, starting in 2004 and reaching its peak in 2006 (Worsley et al. 2006). The object increased its flux density by a factor of 3 in about 4 months (in the source rest frame).

The radio structure of J1430+4204 at the milli-arcsecond (mas) scale is predominantly compact as revealed by Very Long Baseline Interferometry (VLBI) imaging observations (e.g. Paragi et al. 1994, Helmboldt et al. 2007). A weak extension to the bright compact core is also seen in the W-SW direction.
Total flux density outbursts are usually followed by an emergence of a new jet component in the VLBI images of radio AGNs. By observing J1430+4204 after the brightening, we aimed at detecting a new component in a hope to have a zero-epoch point for a later measurement of its apparent proper motion. A study of jet kinematics at such a high redshift would have been interesting since the best-observed sample in the 15-GHz MOJAVE survey (Lister et al. 2007) is restricted to $z < 3.5$.

2. Observations and data processing
We observed J1430+4204 for 8 hours at 15 GHz with the ten 25-m diameter radio telescopes of the NRAO Very Long Baseline Array (VLBA) on 15 Sep 2006. We also found a similar full-polarization experiment (code BY019) in the NRAO data archive. These observations were done on 23 Feb 2005, prior to the brightness peak. We performed standard VLBI calibration, imaging and model-fitting procedures for both data sets using the NRAO Astronomical Image Processing System (AIPS) and the Caltech Difmap program. Our total intensity images are displayed in Fig. 1. The fractional linear polarization of the VLBI core was $\sim 1\%$ and $2\%$ at the first and second epoch, respectively.

The source total flux density at 15 GHz was monitored at the Ryle Telescope (Fabian et al. 1999). The light curve is shown in Fig. 2.

![Figure 1. 15-GHz VLBA images of J1430+4204 on 23 Feb 2005 (left) and 15 Sep 2006 (right). In the left image, the peak brightness is 200 mJy/beam, the restoring beam is 1.17 mas $\times$ 0.52 mas at the position angle PA = $-3.8^\circ$. In the right image, the peak brightness is 159 mJy/beam, the restoring beam is 1.22 mas $\times$ 0.58 mas at PA = $-11.95^\circ$. In both cases, the lowest contour levels are at 0.3 mJy/beam, the positive contours increase by a factor of 2.](image)

3. Determination of the source parameters
We used three methods for computing the following parameters of J1430+4204: the apparent speed of a possible blob in the jet, $\beta_{\text{app}} = \frac{\beta \sin \theta}{1 - \beta \cos \theta}$; the Doppler factor, $\delta = \frac{1}{\Gamma(1 - \beta \cos \theta)}$; and the Lorentz factor, $\Gamma = \frac{\beta^2 + \delta^2 + 1}{2\delta^2} = (1 - \beta^2)^{-1/2}$. Here $\beta < 1$ is the bulk speed of the material in the jet, expressed in the units of the speed of light $c$. For the jet angle to the line of sight, $\theta = \arctan \left( \frac{2\beta_{\text{app}}}{\beta_{\text{app}}^2 + \delta^2} \right)$, we assumed $3^\circ$ as found from bulk Comptonization modeling of the observed X-ray spectrum of J1430+4204 (Cellotti et al. 2007) .

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Figure 2. The 15-GHz flux density vs. time for J1430+4204 from the Ryle Telescope monitoring (G. Pooley, priv. comm.). The points are connected in the flaring phase for clarity. Solid vertical lines mark the times of the two VLBA observations, the filled circles correspond to the measured VLBI flux densities. Dashed lines mark calendar years as indicated.

The most important physical parameter characterizing the jet flow is the bulk Lorentz factor ($\Gamma$). We are also interested in the apparent tangential velocity of the putative blob in the jet which we translate into proper motion. The distance scale at this redshift is 6.588 pc/mas (assuming a cosmological model with $H_0 = 0.71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_\Lambda = 0.73$ and $\Omega_M = 0.27$).

3.1. Parameters from the radio variability
We fitted an exponential function to the brightest flare in the flux density curve (Fig. 2) and determined the variability brightness temperature (Hovatta et al. 2009). Furthermore, we took the intrinsic brightness temperature as $T_{b,\text{int}} = 5 \times 10^{10}$ K, which assumes equipartition between the particles and the magnetic field in the radio-emitting region (Readhead 1994). We then calculated the so-called variability Lorentz factor and the apparent speed.

We obtained $\Delta S = 412$ mJy for the flare amplitude and $\tau = 458.4$ d for the rise time. These led to the variability brightness temperature $T_{b,\text{var}} = 4.1 \times 10^{13}$ K, $\delta_{\text{var}} = 9.4$, $\beta_{\text{app, var}} = 2.4$, $\Gamma_{\text{var}} = 5.1$. The apparent proper motion of the jet component is $\mu = 0.03$ mas/year. This means that during the time between the two VLBA observations ($\Delta T \simeq 570$ d) the supposed blob had moved by $\simeq 0.05$ mas. This angular displacement is below the limit which we can possibly detect with the VLBA at this wavelength ($\sim 0.1$ mas).

3.2. Parameters from the brightness temperature measured with VLBI
We fitted circular Gaussian brightness distribution models to the VLBI visibility data at 15 GHz at both epochs. This gave us $T_b \simeq 1.2 \times 10^{12}$ K brightness temperatures. It corresponds to a Lorentz factor of $\Gamma \simeq 10$, if we again assume the equipartition value for the intrinsic brightness temperature $T_{b,\text{int}}$. This method also predicts a proper motion of $\mu = 0.03$ mas/year.
3.3. Parameters from the inverse Compton process
By assuming that the observed X-ray flux of an AGN is of the inverse Compton origin, we can estimate the Doppler factor (Guijosa & Daly 1994). For J1430+4204, we took the X-ray data from Celotti et al. (2007). The formula for the Doppler factor is

\[ \delta_{IC} = f(\alpha)(1 + z)S_m \times \left[ \frac{\ln(\nu_b/\nu_{op})}{S_X\theta_d^{5+3\alpha} \nu_{op}^{5+3\alpha}} \right]^{1/(4+2\alpha)} \] (1)

where \( f(\alpha) = -0.08\alpha + 0.14 \), \( S_m \) is the radio flux density, \( \nu_b \) is the synchrotron high-frequency cutoff assumed to be \( 10^5 \) GHz. The observed frequency of the radio peak is \( \nu_{op} = 15 \) GHz, the X-ray flux density is \( S_X = 3.7 \times 10^{-7} \) Jy taken at \( \nu_X = 5.2 \) keV, \( \alpha = -0.4 \) is the optically thin spectral index where the \( S_\nu \propto \nu^\alpha \) convention is used, and \( \theta_d \) is the angular diameter of the source in mas. This third method also provided \( \mu \approx 0.03 \) mas/year for the jet component proper motion.

4. Discussion and conclusion
The high-redshift blazar J1430+4204 produced an exceptional radio flux density outburst in 2006 (Fig. 2). We imaged the source with the VLBA at 15 GHz after the time of the flux density peak, and also analyzed the archive VLBA data taken during the rise of the total flux density curve. At both epochs, the mas-scale radio structure of the source was similar: a compact core and a weak extension to S-SW (Fig. 1). The core could be fitted with circular Gaussian components with sizes of 0.076 mas and 0.060 mas (full width at half maximum) on 23 Feb 2005 and 15 Sep 2006, respectively. The comparison of the total and VLBI flux densities at the first epoch (Fig. 2) suggests that \( \sim 50 \) mJy could be attributed to the radio emission extending to more than a few mas.

Based on our VLBA imaging, we do not detect any new separate jet component to be associated with the outburst. Assuming a small jet angle to the line of sight, we used three different methods to calculate the expected proper motion of such a component. These gave consistently small values of the proper motion. We conclude that our time base and angular resolution were insufficient to distinguish any new blob in the jet. Our estimates for the bulk Lorentz factor (\( \Gamma \approx 5 \) – 10) are comparable with the typical values found for other blazars (e.g. Hovatta et al. 2009).

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