A detailed study of the coreshift effect in the blazar 3C 454.3

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ABSTRACT

We study the opacity-driven shift of the apparent parsec-scale radio core position (the "coreshift effect") in the blazar 3C454.3 during its 2008 flare. The effect is investigated using independent techniques: cross-correlation analysis of single-dish 4.8-37 GHz radio light curves and 4.6-43 GHz VLBA data analysis. We estimate the magnetic field strength in the 43 GHz core as of *B*~0.07 G, and jet velocity of 0.7 mas/yr.

INTRODUCTION

The blazar 3C 454.3 (2251+158) is one of the most prominent quasar-type sources in the sky. It shows strong variability in all spectral bands from radio to gamma. The SED of 3C 454.3 shows synchrotron and inverse Compton to be the dominating radiation mechanisms.

The structure of most blazars, including 3C 454.3 (Fig. 1), is dominated by a bright, unresolved or barely-resolved feature called the core. We consider here the core to be a surface where optical depth of the jet synchrotron radiation $\tau_\nu \approx 1$ - the "photosphere" (e.g. Königl 1981). This jet model predicts that the position of the photosphere depends on the observing frequency. This is known as the "core shift" effect and it was first observed by Marcaide & Shapiro (1984) in the quasar pair 1038+528 A, B. Measurements of this frequency-dependent core position shift provide an information about the physical conditions and structure of ultracompact blazar jets (Lobanov 1998 [L98], Hirotani 2005 [H05], O'Sullivan & Gabuzda 2009 [O09]).

The core shift effect also has important consequences for ultra-high precision astrometry and spacecraft navigation with VLBI. It should be taken into account when constructing VLBI spectral index and Faraday rotation maps.

In this work we adopt the average geometrical and kinematical values measured in 3C454.3 by Jorstad et al. (2005): $\theta = 1.3^\circ$, $\varphi = 0.8^\circ$, $\delta = 24.6$, $\Gamma_j = 15.6$.

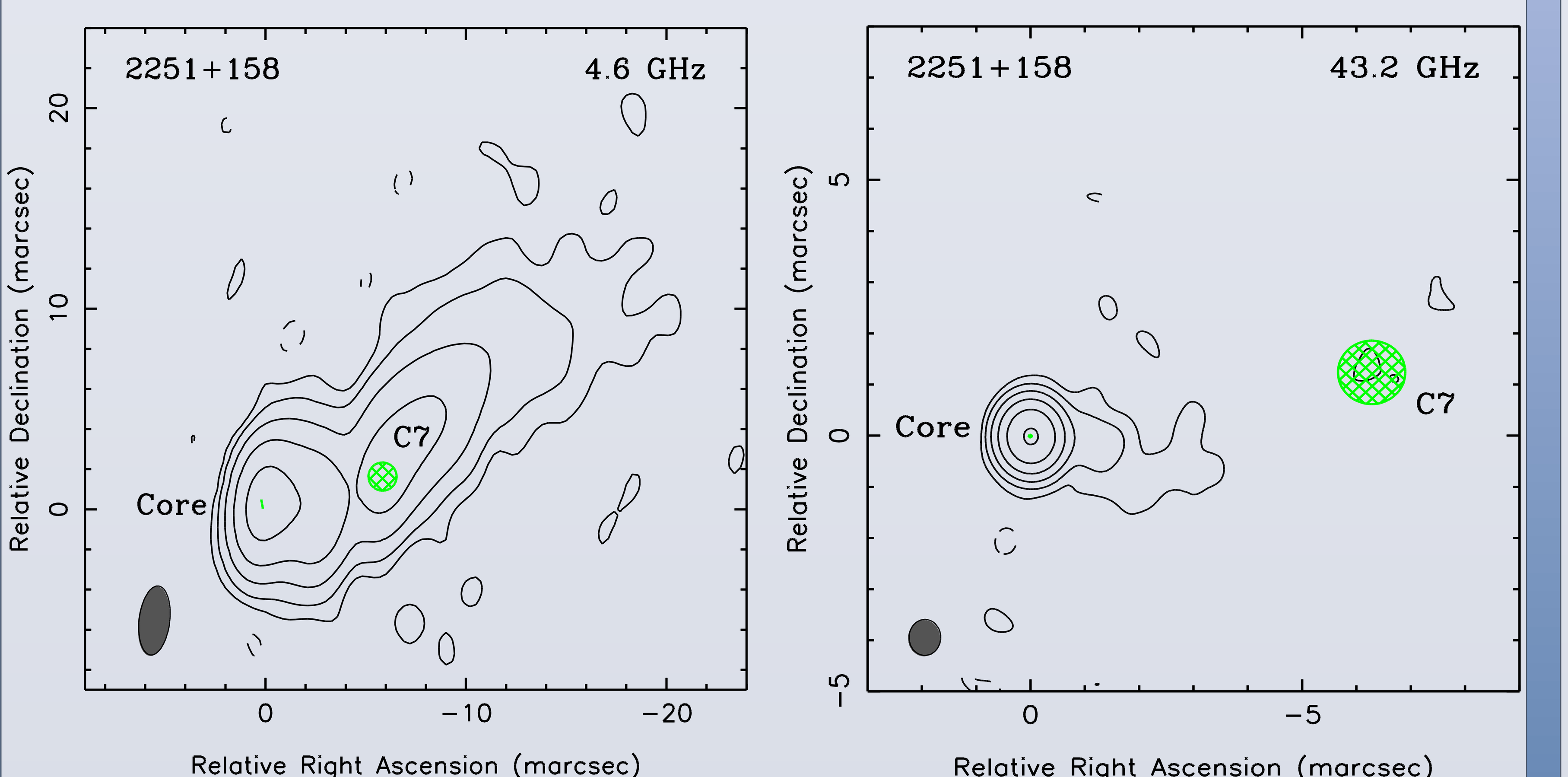


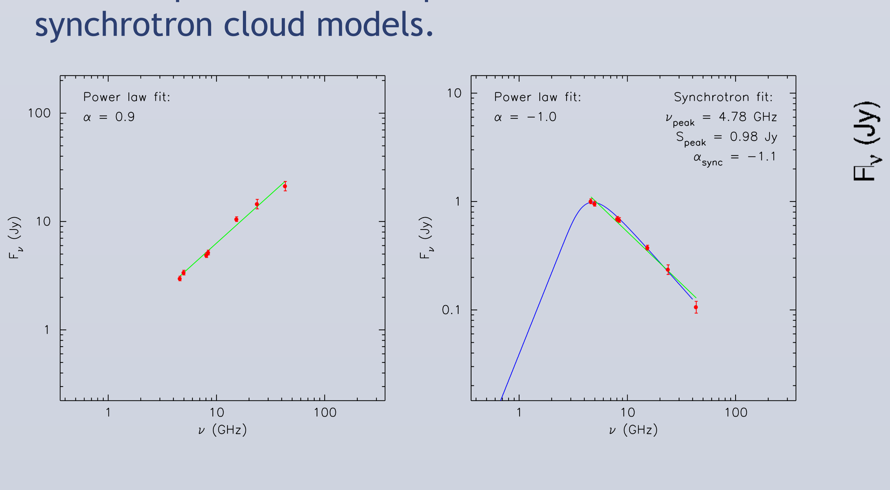
Fig 1. Naturally weighted total intensity CLEAN images of 3C 454.3. The image peaks are 3.3 and 23.5 Jy/beam for the 4.6 and 43.2 GHz image, respectively. The contours starting at 6 mJy/beam are a factor of 4 apart for all images. The beam is plotted in the lower left corner of each image.

OBSERVATINAL DATA

3C 454.3 was observed on October 2, 2008 with the NRAO's Very Long Baseline Array (VLBA) simultaneously at seven frequencies (4.6, 5.0, 8.1, 8.4, 15.4, 23.8 and 43.2 GHz) in the framework of a survey of parsec-scale radio spectra of twenty γ-ray bright blazars (Sokolovsky et al. 2010).

Single-dish flux density monitoring observations of 3C 454.3 obtained with the 26-m UMRAO radio telescope at 4.8, 8.0 and 14.5 GHz, 14-m Metsahovi telescope at 22 and 37 GHz and the 22-m RT-22 CrAO telescope at 22 and 37 GHz were adopted from (Volvach et al. 2011).

Fig 2. Core and reference component C7 spectra derived from uv-modeling. The observed spectra are compared to the power law and uniform synchrotron cloud models.



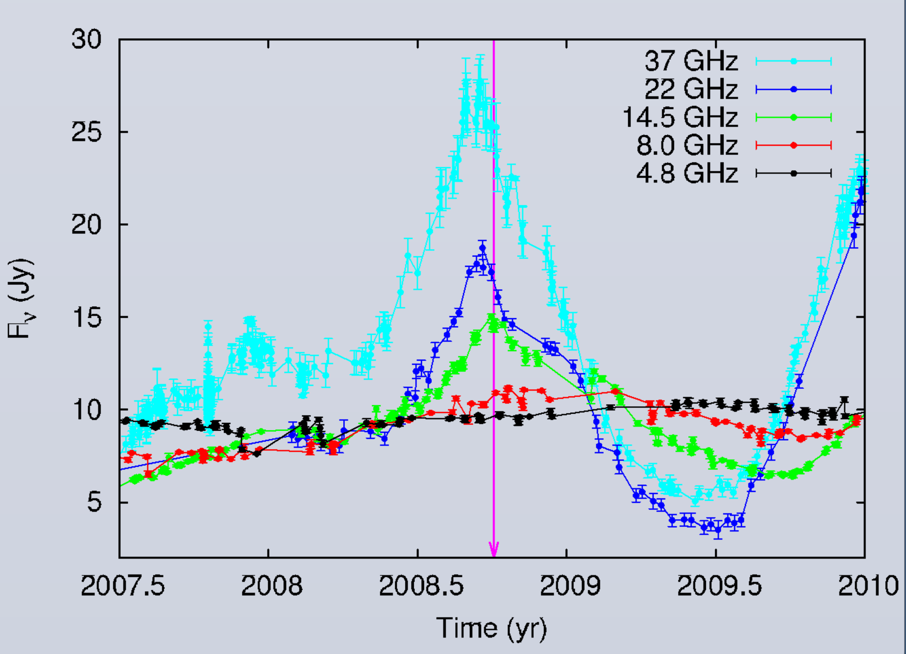


Fig 3. Radio light curves of the 2008 flare. The arrow indicates VLBA observation epoch.

ν (GHz)	$\vert\vec{r}\vert$ (mas)	r_c (mas)	W (mas)	ΔT (year)
43.2	0.0	5.979 ± 0.046	0.055	...
36.8	...	...	...	0.0
23.8	0.02 ± 0.01	5.944 ± 0.013	0.071	...
22.2	...	...	...	0.04 ± 0.03
15.4	0.06 ± 0.04	5.936 ± 0.009	0.099	...
14.5	...	...	...	0.13 ± 0.03
8.4	0.30 ± 0.04	5.899 ± 0.007	0.169	...
8.1	0.21 ± 0.04	5.900 ± 0.008	0.143	...
8.0	...	...	...	0.39 ± 0.04
5.0	0.54 ± 0.06	5.756 ± 0.005	0.500	...
4.8	...	...	...	0.75 ± 0.07
4.6	0.60 ± 0.06	5.757 ± 0.004	0.456	...
$a =$	6.0 ± 2.6	-3.3 ± 3.0	4.6 ± 2.5	6.2 ± 1.4
$b =$	-0.03 ± 0.03	5.96 ± 0.04	0.05 ± 0.01	-0.06 ± 0.02
$k =$	0.68 ± 0.13	0.56 ± 0.22	0.60 ± 0.09	0.81 ± 0.09

Column designation: Col. 1 – frequency, Col. 2 – core position shift from cross-correlation analysis, Col. 3 – core separation from the reference jet component, Col. 4 – core size, Col. 5 – light curves time delay. The last three rows present best values of coefficients in the $a\nu^{-1/k} + b$ fit to the data in the corresponding columns.

DATA ANALYSIS AND RESULTS

We study the core shift effect using four different methods: VLBI core position offset measured with brightness distribution modeling, two-dimensional image cross-correlation technique, VLBI core size dependence on frequency, and time-delay analysis of single-dish radio light curves. The last method assumes that the flare at a given frequency ν_{obs} has its peak quite near the jet location, where we observe the core at this frequency and that the flow speed is constant; this approach is considered by Bach et al. (2006) and Kudryavtseva et al. (2011). The distance of the core from the jet origin $r_c(\nu)$, the core size $W(\nu)$, and the light curve time lag $\Delta T(\nu)$ all depend on the observing frequency ν as $r_c(\nu) \propto W(\nu) \propto \Delta T(\nu) \propto \nu^{-1/k}$. The resulting measured offsets and fit parameters are presented in the table above. All the methods provide consistent results, giving a value of core shift parameter k<1.

The magnetic field strength B and particle density N are declining with distance from the jet origin, r, according to the power law: $B = B_1(r/r_1)^{-m}$, $N = N_1(r/r_1)^{-n}$ (here B_1 and N_1 are values at r_1=1 pc from the jet base). Next we consider two possible situations:

1) Ambient medium pressure on the jet is negligible. In this case we can use formulas from L08, H05 and O09 to estimate the m, n values, the core size and magnetic filed strength. Assuming equipartition we obtain n=2m≈1.6; B_1=0.4±0.2 G. The 43 GHz core size is ~9 pc, and its magnetic field strength is 0.07±0.04 G.
2) The external pressure is non-negligible and has a non-zero gradient along the jet. The measured value of k may be related to the pressure gradient (L98) resulting in m_p≈0.4 and n_p≈2.2. The jet of 3C 454.3 gradually "opens up" being accelerated.

On the equipartition assumption, we also calculate the total jet power (H05): for an electron-positron jet and k=0.7, the total kinetic power is about ~10^{44} ergs/s.

The apparent jet velocity is determined by comparing the time lags between the flare peaks at different frequencies with the VLBI core position shift between the respective frequencies: $\mu_{app}=\Delta r/\Delta T \simeq 0.7$ mas/yr.

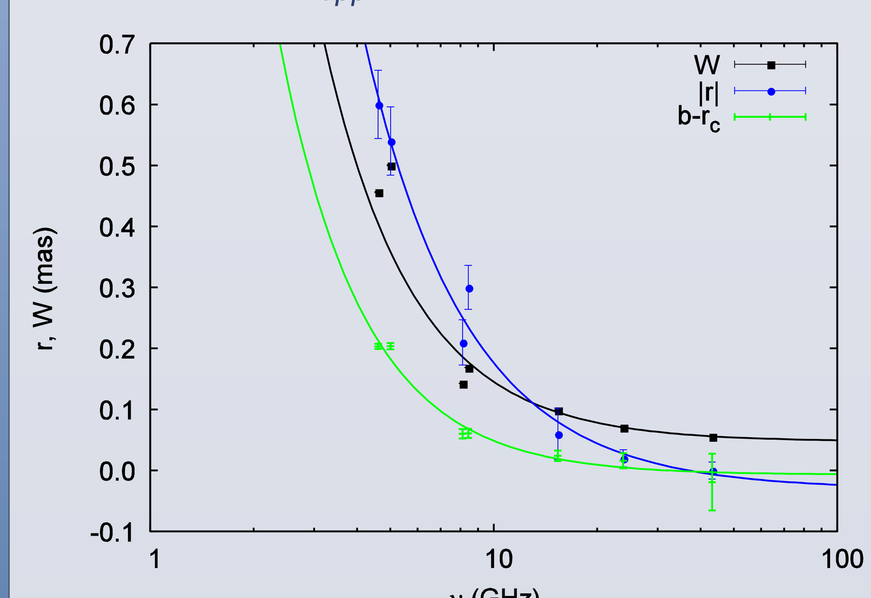


Fig 4. Measured values of the core shift (|r|), core to C7 component separation (r_c), and core width (W) as a function of frequency ν (see the table).

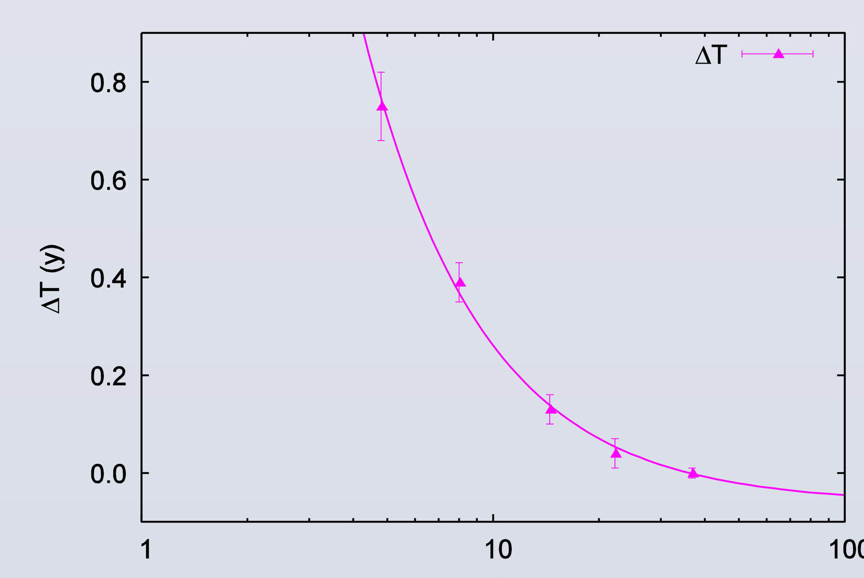


Fig 5. Measured time lags of the radio light curves of the 2008 flare as a function of frequency ν (see the table).

CONCLUSIONS

The value of core shift parameter k obtained using different techniques demonstrates their self-consistency and supports the standard Königl model as an appropriate description of jet physics in the VLBI core region. The fact that k is found to be in the range (0.6–0.8) is consistent with the synchrotron self-absorption being the dominating opacity mechanism in the jet of 3C 454.3. Single-dish data may provide an important independent information about the innermost jet regions.

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