

Rapid and correlated variability of blazar S5 0716+71 from radio- to sub-mm bands

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The BL Lac object S5 0716+71 was a target of a coordinated and global multi-frequency campaign to search for rapid and correlated variability, and signatures of the inverse-Compton (IC) catastrophe. Here, we present first results obtained from a combined analysis of the cm- to sub-mm observations over a period of seven days, aiming at a detailed study of the intra- to inter-day variability characteristics and to obtain constraints on the variability brightness temperatures and Doppler factors comparing the radio data with the high-energy emission recorded by INTEGRAL. A more detailed description of the whole cm- to sub-mm observations and our analysis/results will be presented in a forthcoming paper. Our analysis reveals the source to be in a particularly short-term variability phase when compared to the past with a correlated $\gtrsim 4$ day time scale amplitude increase of up to 35%, which is systematically more pronounced towards higher frequencies. The obtained frequency-dependent variability amplitudes and time lags contradict expectations from interstellar scintillation and strongly suggest an intrinsic origin of this inter-day variability. A 7-day spectral-evolution study indicate time-variable synchrotron self-absorption and expansion of the emission region, consistent with standard models. Assuming relativistic boosting, our different estimates of the Doppler factor yield robust lower limits of $D_{var,IC} > 5-22$ using the IC-limit and $D_{var,eq} > 8-33$ using the equipartition argument. Although high, these values are in a good agreement with Doppler factors obtained from recent VLBI studies and from the IC Doppler factors $D_{IC} > 14-16$ derived based on the X-ray emission seen by INTEGRAL at 3–200 keV.

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1. Introduction

Blazars showing the ‘classical’ type-II IntraDay Variability (IDV) in the radio regime ([17], [6]) display flux density variations on time scales of $\lesssim 0.5$ –2 days and variability amplitudes ranging from a few up to 30 percent. In order to explain the observed variations, intrinsic (e.g. shock-in-jet) as well as extrinsic models (i.e. interstellar scintillation) are discussed. If the observed IDV is interpreted as source-intrinsic, the short variability time scales imply ultra-compact emission regions with extremely high photon densities, leading to apparent brightness temperatures largely exceeding the inverse Compton (IC) limit for incoherent synchrotron radiation of 10^{12} K ([7], [13]) by several orders of magnitude (see also [16]). In order to bring these apparent brightness temperatures down to the IC-limit, rather extreme relativistic Doppler-boosting corrections (with Doppler factors $\delta > 100$) would be required. As such high Doppler factors (and related bulk Lorentz factors) are not observed in AGN jets, alternate jet (and shock-in-jet) models are discussed that make use of special, non-spherical geometries and allow for additional relativistic corrections (e.g. [15], [11]). It is also possible that the brightness temperatures are intrinsically high and are caused by some kind of coherent process (e.g. [3]). Further, it is unclear at present, if the IC-limit might actually be violated for brief periods of time (e.g. [14]). The quasi-periodic and persistent violation of this limit (on time scales of hours to days) would then imply subsequent Compton catastrophes, each leading to outbursts of IC-scattered radiation via second order scattering, which should be observable in the X-/ γ -ray bands ([7], [4]). Such efficient cooling flares would then rather quickly restore the local brightness temperature in the source (see also [10]).

In order to search for multi-frequency signatures of such short-term IC-flashes occurring at hard X-ray and soft γ -ray energies, the prototypical IDV source S5 0716+71 ($z > 0.3$) was targeted with a large multi-frequency campaign carried out between October 2003 and May 2004. The core-campaign was centred around a 500-ksec-INTEGRAL¹ pointing of the source between November 10 and 17, 2003. In order to obtain as good as possible time and frequency coverage during the INTEGRAL observations, quasi-simultaneous flux-density, polarization and VLBI observations at radio, millimeter, sub-millimeter, infrared and optical wavelengths were organized. An initial description of this large campaign with a first presentation of the results of the INTEGRAL observations and selected radio/optical variability curves was given by [10]. The analysis of the 3-mm and 1.3-mm intensity and polarisation measurements performed with the IRAM 30-m radio-telescope on Pico Veleta (PV) were presented by [1].

In the following, we show and discuss first results of our combined analysis of the radio to (sub-) mm total-intensity data acquired during the time of the core-campaign (November 10–17, 2003). In particular, we concentrate on the intra- to inter-day variability behaviour of S5 0716+71 (hereafter 0716+714) as deduced from the densely time-sampled total-intensity data obtained with the Effelsberg 100-m (EF) and PV with special regard to a possible violation of the IC-limit. These data sets are combined with the available (sub-) millimeter data to determine the broad-band variability and spectral characteristics of 0716+714. Further, we discuss the possible origin of the observed variations as well as present Doppler factors calculated through various methods in comparison with the high-energy emission observed by INTEGRAL.

A detailed description of all observations and data sets as well as our full analysis and results

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Table 1: Summary of the participating radio observatories and their observing wavelengths.

Radio telescope & Institute	Location	λ_{obs} [mm]
WSRT (14×25 m), ASTRON	Westerbork, NL	210, 180
Effelsberg (100 m), MPIfR	Effelsberg, D	60, 28, 9
Pico Veleta (30 m), IRAM	Granada, E	3.5, 1.3
Metsähovi (14 m), MRO	Metsähovi, Finland	8
Kitt Peak (12 m), ARO	Kitt Peak, AZ, USA	3
SMTO/HHT (10 m), ARO	Mt. Graham, AZ, USA	0.87
JCMT (15 m), JAC	Mauna Kea, HI, USA	0.85, 0.45

including polarisation will be presented in a forthcoming paper ([5]).

2. Observations and data analysis

In total, seven radio observatories were involved, covering a frequency range from 1.4 to 666 GHz (corresponding to wavelengths ranging from 21 cm to 0.45 mm). In Table 1, the participating observatories and their frequency coverage are summarized. Here, we will concentrate on the observations performed with EB (4.85, 10.45, 32 GHz) and PV (86 GHz). At each frequency, the target source and a sufficient number of secondary calibrators were observed continuously with a dense time-sampling of about two flux-density measurements per hour, source and frequency. The data reduction was performed following standard procedures for IDV observations with EB (e.g. [8]). A detailed description of the PV observations and data reduction can be found in [1]. Our individual measurement uncertainties typically lie in the range of $\leq 0.5\text{--}1\%$ up to 10.45 GHz and are a factor of 2–3 higher at 32 GHz. At 86 GHz, a value of $\sim 1.2\%$ was reached ([1]).

In order to study the multi-frequency variability characteristics of the source, each data set was investigated via a statistical variability analysis, based on the following steps: (i) a test for the presence of variability (χ^2 -test), (ii) the measurement of the variability amplitudes and (iii) the determination of the characteristic variability timescales. These methods are described in more detail by [6], [12], [8] and [5]. Further, we performed a detailed cross-correlation (CCF) analysis between all possible frequency combinations as well as constructed (quasi-) simultaneous radio spectra by combining all available total-intensity data for each observing day. Finally, lower limits to the Doppler factor δ were estimated and compared using various methods: (i) δ_{var} as deduced from the variability brightness temperatures, (ii) the equipartition Doppler factor δ_{eq} using calculations of the synchrotron and equipartition magnetic field, (iii) $\delta_{var,eq}$ as derived using the equipartition brightness temperature T_{eq} and (iv) the IC Doppler factor δ_{IC} as calculated from the simultaneous INTEGRAL observations. Our results will be briefly presented and discussed in the following.

3. Results and discussion

In Fig. 1, we plot the flux density measurements of 0716+714 versus time at 4.85, 10.45 and 32 GHz together with the residual flux density variability of the secondary calibrator 0836+714. In addition, we add from [1] the measurements obtained with PV at 86 GHz. A first inspection of the

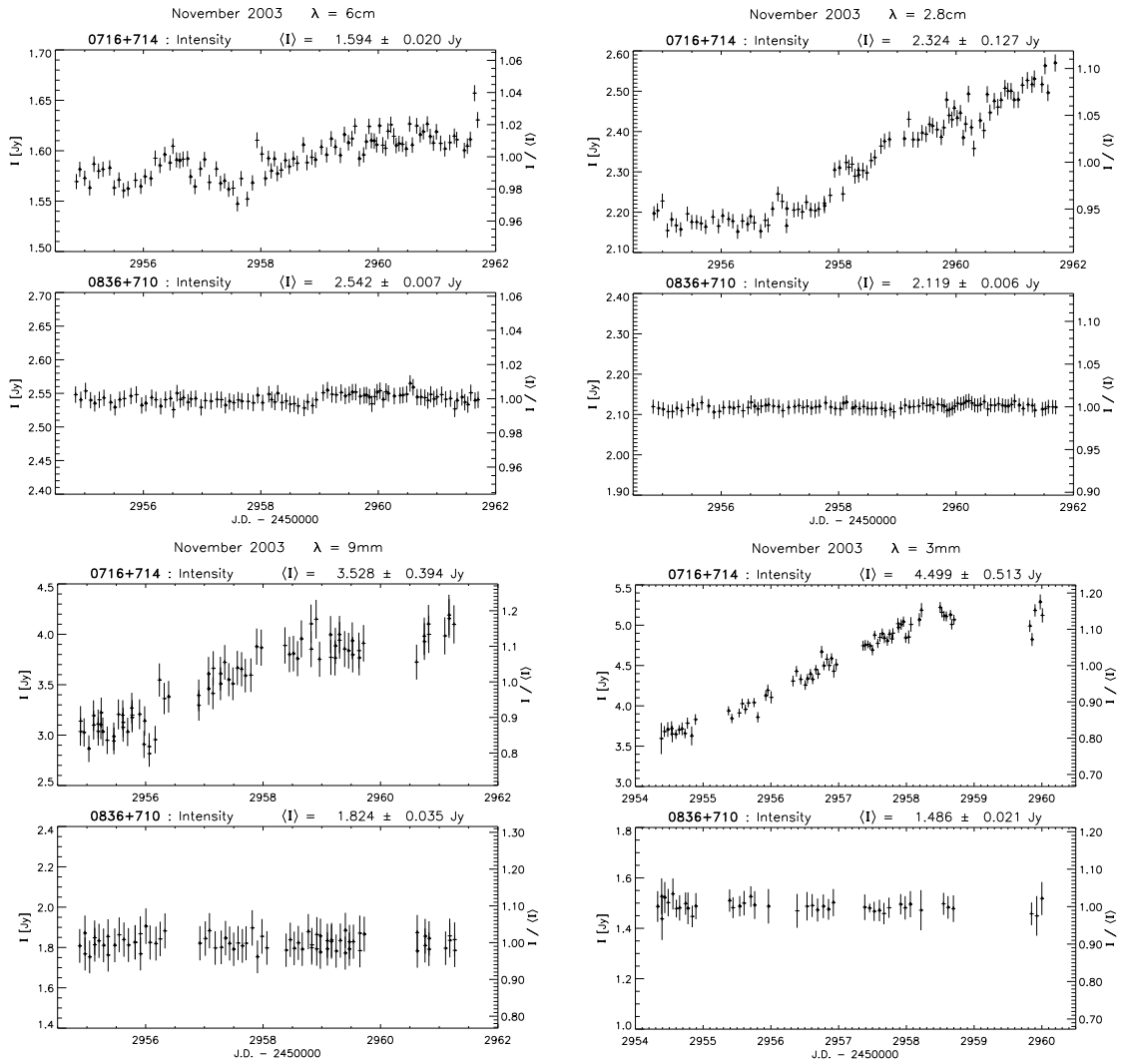


Figure 1: Final light curves of 0716+714 obtained at 60, 28, 9 and 3 mm wavelengths, corrected for all systematic effects. For a direct comparison, the residual variability of the secondary calibrator 0836+714 at each band is presented, which shows remaining peak-to-peak variations of $\sim 1\%$ (60, 28 mm), $\sim 8\%$ (9 mm) and $\sim 6\%$ (3 mm).

light curves shows 0716+714 to be strongly variable when compared to the stationary secondary calibrator. Further, the source appears to be in a particular, short-term variability phase when compared to the usually observed ‘classical’, more rapid IDV pattern. At $\lambda = 60$ mm, 0716+714 shows only few-percent low-amplitude variations followed by a slow (2 day) flux-density increase after J.D. 2452957.6. The peak-to-peak amplitude variations are $\leq 4\%$. The light curves obtained at 28, 9 and 3.5 mm wavelengths are dominated by a much stronger monotonic increase of the flux density over a time range of several days. Here, the $\gtrsim 4$ day time scale amplitude increase reaches up to $\sim 35\%$ at $\lambda = 3$ mm. Our CCF analysis confirms that the variability pattern is strongly correlated across the observing bands with a trend of increasing time lag, τ , towards larger frequency separation. In Fig. 2 (left panel), we plot the $\tau_{60/i}$ time lags for the three observing bands ($i = 28, 9, 3$ mm) versus observing frequency. A clear and systematic trend towards higher frequencies is seen, which

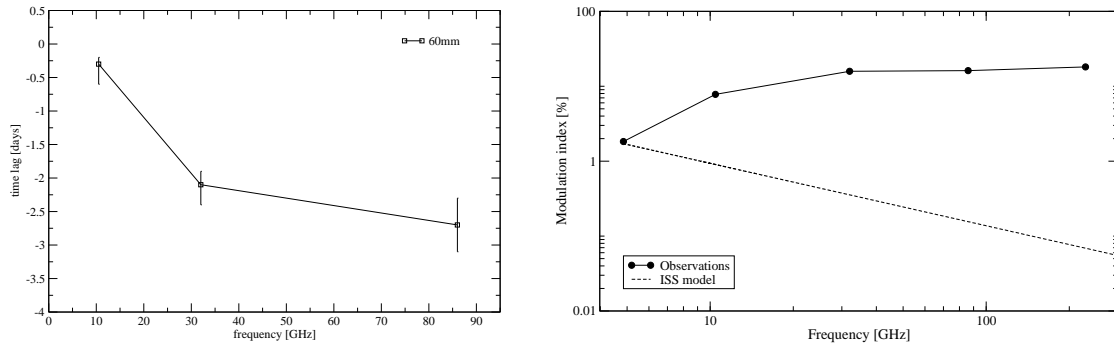


Figure 2: Variability behaviour of 0716+714 across the observing bands. **Left:** relative time lags for the 60-mm combinations versus frequency (see text). **Right:** observed variability amplitudes versus frequency with model predictions for weak interstellar scintillation superimposed. Note the strong discrepancy between model calculations and observed values.

demonstrates that the observed flux density increase occurs first at the higher frequencies and then propagates through the radio spectrum towards lower frequencies. In addition, the variability amplitude is systematically more pronounced towards higher frequencies as seen from Fig. 1 as well as Fig. 2 (right panel). Such ‘canonical’ variability behaviour provides strong evidence for a source intrinsic origin of the observed variability. A similar behaviour is seen in AGN and other compact radio sources over longer time intervals (weeks to years) and is commonly explained by synchrotron-cooling and adiabatic expansion of a flaring component or a shock (e.g. [9]). Furthermore, the observed frequency dependence of the variability amplitudes contradicts our calculations for a standard model of interstellar scintillation, which further supports an intrinsic interpretation (Fig. 2, right panel). The sudden disappearance of the ‘classical’, more rapid IDV behaviour of 0716+714 in the cm-band is most likely caused by opacity effects and related to the overall flaring (and high radio-to-optical) state of the source during the campaign (see also [10]).

Our 7-day spectral-evolution study shows an inverted synchrotron spectrum peaking near

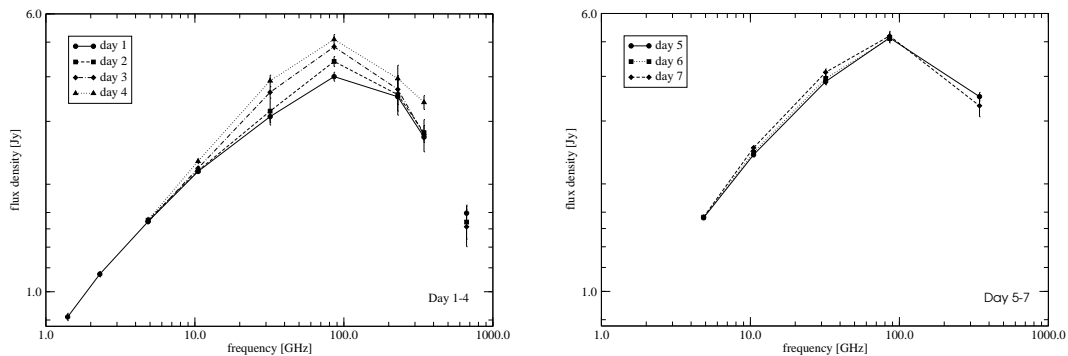


Figure 3: Simultaneous cm- to sub-mm spectra of 0716+714 derived from daily averages of the flux-density measurements obtained during November 11 to 17 using all frequencies. **Left:** the spectra for days 1–4 (November 11–14, J.D. 2452955–58). **Right:** the spectra of days 5–7 (November 15–17, J.D. 2452959–61). The flux density errors are small and when invisible, comparable or smaller than the size of the symbols.

$\nu_m \sim 90$ GHz, with its spectral peak flux continuously increasing during the first 4 days and then remaining nearly constant (see Fig. 3). Slight changes in the daily spectral slopes and the turnover frequency ν_m indicate time-variable synchrotron self-absorption and expansion of the emission region, consistent with standard models. The calculated lower limits to the variability brightness temperatures deduced from the inter-day variations at the different radio bands exceed the 10^{12} K IC-limit by two orders of magnitude in the mm-bands and 3 – 4 orders of magnitude in the cm-bands. Assuming relativistic boosting, our different estimates of the Doppler factor yield robust lower limits of $\delta_{var,IC} > 5 - 22$ using the IC-limit and $\delta_{var,eq} > 8 - 33$ using the equipartition argument. Although high, these values are in a good agreement with Doppler factors obtained from recent VLBI studies ($\delta_{VLBI} = 20-30$, [2]) and from the IC-Doppler factors $\delta_{IC} > 14-16$ we derived using the simultaneous upper limits to the source emission in the INTEGRAL 3–200 keV energy range. The only obtained upper limits to the source emission in the soft γ -ray band (see [10]) imply high Doppler factors in the source as well as the non-detection of a simultaneous strong IC-catastrophe during the period of our observations. Since a strong contribution of interstellar scintillation to the observed inter-day variability pattern can be excluded, we thus conclude that relativistic Doppler boosting seems to naturally explain the apparent violation of the theoretical limits as observed here.

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