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Annual modulation in the IDV timescale of J1128+592

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Short time scale radio variations of compact extragalactic radio quasars and blazars known as IntraDay Variability (IDV) can be explained in at least some sources as a propagation effect; the variations are interpreted as scintillation of radio waves in the turbulent interstellar medium of the Milky Way. One of the most convincing observational arguments in favour of a propagation-induced variability scenario is the observed annual modulation in the characteristic variability time scale due to the Earth's orbital motion. So far there are only two sources known with a well-constrained seasonal cycle. J1128+592 is a recently discovered, highly variable IDV source. Previous, densely time-sampled flux-density measurements with the Effelsberg 100-m radio telescope (Germany) and the Urumqi 25-m radio telescope (China), strongly indicate an annual modulation of the time scale. Here, we summarise the annual modulation model derived using all the measurements, carried out in the last 2.5 years.

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1. Introduction

Quasars and blazars show variability in every observing wavebands, with various time scales ranging from minutes to years. Using the light-travel time argument, one can estimate an upper limit of the size of the emitting region responsible for the variability. In the case of IDV in radio bands the brightness temperature deduced from the size estimation often exceeds the inverse-Compton limit of $\sim 10^{12}$ K. The high brightness temperatures are usually explained via Doppler boosting, however in the case of the short timescale variations of IDV the inferred Doppler boosting factors often contradict to the Doppler boosting factors derived from Very Long Baseline Interferometry (VLBI) observations of quasars and blazars. The latter usually below 50, while the Doppler factors derived from the IDV sources are a couple of hundreds, in extreme cases can reach 1000 (e.g. PKS0405-385 [1]).

To solve this contradiction it was proposed by [2], that the fast variations are not source-intrinsic rather caused by interstellar scintillation (ISS) in the intervening turbulent plasma of the Milky Way. The two most convincing arguments in favour of this explanation are the time-delay measurements and annual modulation of the variability time scale.

Time-delay measurements of the variability pattern arrival time between two sites located at different places of the Earth were successfully performed in the case of PKS0405-385 [4], J1819+3845 [3] and PKS1257-326 [5]. These measurements however **are** only feasible in the case of IDV sources showing extremely rapid variations (also called intra-hour variable sources), when changes in the flux density can be detected (with high accuracy) within tens of seconds [6].

Annual modulation of the variability timescale is caused by the Earth orbital motion around the Sun. The variability timescale is inversely proportional to the relative velocity between the observer and the scattering material (e.g. [15]). Since the observer's velocity have a yearly modulation due to the orbit of the Earth, this yearly modulation can also be observed in the variability timescale of the IDV source. Such effect was observed in J1819+3845 [7] and PKS1257-326 [5]. In a few other IDV sources, such as B0917+624 [8, 9], PKS0405-385 [1], and B0954+658 (Fuhrmann et al. in prep.), the observed variability timescales do not show such a clear effect, and a possible seasonal pattern is either not present or is smeared out. For two sources, B0917+624 [10] and PKS0405-385, so called episodic IDV (e.g. [1]) is observed, where previously observed pronounced IDV, either temporarily disappears (PKS0405-385), or even ceases (B0917+624). This makes it difficult to prove beyond doubt the existence of any annual modulation pattern. We note that such episodic IDV can also be due to changes of the source structure (i.e. expansion of previously scintillating structure components) or due to changes in the properties of the scattering plasma.

To establish convincingly an annual modulation pattern, the source has to be observed regularly during the course of the year and for several years. To facilitate the measurement of a characteristic variability time scale, the duration of an individual IDV session must be long enough, so that several "scintillation" events can be observed. Within the scheduling constraints of large observatories, the regular observations of fast scintillators, which vary on time scales of a few hours or less, are easier to perform than for the slower (more common) IDV sources. For these sources, IDV observations (lasting at least 3-4 days) cannot be performed on a regular basis throughout the year with oversubscribed telescopes.

In this paper, we present the data of J1128+592 obtained in 2007 together with the earlier

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measurements. We also present the preliminary results of Very Long Baseline Array (VLBA) observation of J1128+592.

2. IDV observations and data reduction

J1128+592 was observed with the Max-Planck-Institut für Radioastronomie (MPIfR) 100-m Effelsberg radio telescope (at 2.70, 4.85 and 10.45 GHz) and with the Urumqi radio telescope (at 4.85 GHz) during $\approx$ 2.5 years in so far 19 observing sessions, each lasting several days. The results of the first ten epochs of observations are already published in [11]. Preliminary results of four additional epochs are published in [18].

The low-noise 4.85 GHz receiver, a new receiver back-end and new telescope driving software for the Urumqi telescope were provided by the MPIfR. A detailed technical description of the receiver system and the telescope is given in e.g. [12].

At both telescopes, the flux-density measurements were performed using the cross-scan technique, in which the telescope is moved repeatedly (4 – 8 times) in azimuth and in elevation over the source position. Each such movement is called a subscan. After baseline subtraction, a Gaussian curve was fitted for each subscan to the resulting slice across the source. For each scan, the averaged and pointing corrected peak amplitude of the Gaussian curve yielded a measure of the source flux density. Then the systematic elevation and time-dependent gain variations were corrected, using the combined gain curves and gain-transfer functions of calibrator sources of known constant flux density. The measured flux densities were then tied to the absolute flux-density scale. The absolute flux-density scale was determined from repeated observations of the primary calibrators e.g. 3C 48, 3C 286, 3C 295 and NGC 7027 and using the flux-density scale of [13] and [14].

A more detailed description of the data reduction and the comparison of accuracy reached by the two telescopes is given in [11].

For the variability analysis, we follow the method introduced by [16]. The amount of variability in a light curve is described by the modulation index **and the variability amplitude**. The modulation index is defined as $m = 100 \cdot \frac{\sigma}{\langle S \rangle}$, where $\langle S \rangle$ is the flux density **averaged over the duration of the observation, typically 2 to 4 days**, and σ is the standard deviation of the flux density. **Since for each experiment the variability indices m of the target and m_0 of the calibrator(s) are derived from mutually calibrated data trains with almost identical time coverage, the average modulation index of the calibrator sources (m_0) provides a conservative estimate of the overall calibration accuracy. We note that m_0 may include small amounts of residual scatter (see Table 1, col. 5) and therefore is also a reliable measure of the overall calibration accuracy and remaining residual systematic effects of each observation. For each experiment, the error of the modulation index depends on the duration of the observation and the sampling interval (see [11] and references therein). The uncertainty of the here reported modulation indices was found to range between 10 % to 30 % for a given value. The variability amplitude is defined as the noise-bias corrected 3-σ value of the modulation index: $Y = 3\sqrt{m^2 - m_0^2}$ and thus facilitate to compare the variations observed at different epochs.**

To determine the characteristic variability time scale, we made use of the structure function (for a definition see e.g. [17]), the autocorrelation function and the light curve itself. We defined the characteristic variability time scale by the time-lag, where the structure function

reaches its saturation level. In theory, this corresponds to the first minimum of the autocorrelation function. We also compared these with the average peak-to-trough time derived from the light curve (for details see [11]).

3. Results

The results of the observations of J1128+592 are tabulated in Table 1. We list for all the epochs the variability parameters: average modulation index of calibrators (m_0), average flux density of J1128+592 ($\langle S \rangle$), modulation index of J1128+592 (m) and the scintillation time scale ($t_{\rm scint}$). The variability of J1128+592 is highly significant in all observing epochs, in all frequencies.

For those epochs where we have simultaneous multi-frequency measurements[1], Y shows a systematic frequency dependence: it decreases in magnitude from 2.70 GHz to 10.45 GHz. This frequency dependence is consistent with the ISS theory, which explains the IDV phenomenon by ISS in the so-called weak regime (e.g. [15]), where the strength of variability decreases with increasing frequency. (For a detailed quantitative analysis see [11]).

In the last column of Table 1, the scintillation time scales are given. At one epoch (2006 December 16-18), there were several gaps in the data due to unfortunate weather conditions, therefore we were not able to reliably derive a time scale. At the epoch of 2007 April 20-23, there is an indication of a faster variations in the light curve, therefore we listed both time scale values. However, the faster time scale might be caused by the uneven sampling. There are three gaps in the dataset, in between them the source was observed for an average duration of about 0.5 days, which can explain the detection of the 0.5 day-long time scale.

The 4.85 GHz time scales range between 0.1 day and 1.8 day. In Fig. 1, 4.85 GHz light-curves are displayed from 8 different epochs - four pairs of variability curves which are separated by approximately one year.

- In the first subplot 14-17.08.2005 and 19-25.08.2006
- In the second subplot 16-19.09.2005 and 23-27.09.2006
- In the third subplot 27-31.12.2005 and 16-18.12.2006
- In the fourth subplot 28.04-02.05.2006 and 29.04-03.05.2007.

In three pairs of epochs, the similarities in the variability time scales can be recognised. Even in the 2006 December epoch, where we were unable to determine a time scale, the variations seems to be similarly fast as approximately a year before. There is difference in the time scale in the September epochs, where a slower variability can be seen in 2006 than in 2005. However the measurements are much noisier in the later epoch.

As we did previously in [11], we try to explain the changes in the variability time scales with an annual modulation model. The best fit to the original data was achieved using the anisotropic annual modulation model of [5], which is represented by the solid curve (labelled (a)) in Fig. 2. **Including the results of the new observations, we obtained the fit labelled (b), represented by**

[1]Except for the observation in 2005 May, when the high-frequency measurements were shorter due to bad weather conditions.

Epoch	DOY	R.T.	ν (GHz)	m_0 (%)	$\langle S \rangle$ (Jy)	m (%)	t_{scint} (day)
25-31.12.2004[a]	361	E	4.85	0.4	0.570	10.9	0.30 ± 0.10
13-16.05.2005[a]	134	E	4.85	0.5	0.611	2.2	0.88 ± 0.10
13-16.05.2005[a]	134	E	10.45	0.6	0.730	3.8	0.90 ± 0.15
14-17.08.2005[a]	227	U	4.85	0.6	0.682	5.9	0.90 ± 0.30
16-19.09.2005[a]	260	E	4.85	0.6	0.719	2.9	0.55 ± 0.15
27-31.12.2005[a]	363	U	4.85	1.2	0.713	7.9	0.35 ± 0.08
29-30.12.2005[a]	363	E	2.70	0.3	0.524	6.8	0.54 ± 0.05
29-30.12.2005[a]	363	E	4.85	0.4	0.725	7.2	0.34 ± 0.06
29-30.12.2005[a]	363	E	10.45	1.4	0.826	3.2	0.22 ± 0.03
10-12.02.2006[a]	42	E	2.70	0.3	0.526	10.2	0.59 ± 0.10
10-12.02.2006[a]	42	E	4.85	0.4	0.723	6.8	0.10 ± 0.05
15-18.03.2006[a]	75	U	4.85	0.5	0.668	5.7	0.37 ± 0.10
28.04-02.05.2006[a]	120	E	2.70	0.4	0.484	17.7	1.85 ± 0.10
28.04-02.05.2006[a]	120	E	4.85	0.5	0.639	9.0	1.52 ± 0.15
28.04-02.05.2006[a]	120	U	4.85	0.5	0.645	7.0	1.51 ± 0.25
10-13.06.2006[a]	162	U	4.85	0.5	0.595	4.1	0.51 ± 0.08
14-18.07.2006[a]	196	U	4.85	0.7	0.601	5.8	0.60 ± 0.25
19-25.08.2006	234	U	4.85	0.7	0.655	1.4	1.20 ± 0.20
23-27.09.2006	268	U	4.85	0.8	0.613	2.3	1.30 ± 0.40
16-18.11.2006	321	U	4.85	0.6	0.551	4.7	1.10 ± 0.10[b]
16-18.12.2006	321	E	4.85	0.5	0.522	3.0	–[c]
13-15.01.2007	14	E	4.79[d]	0.4	0.505	5.2	0.40 ± 0.14
30.03-01.04.2007	89	E	4.85	0.3	0.455	2.9	0.45 ± 0.05
20-23.04.2007	112	U	4.85	1.0	0.437	2.2	$(0.50 \pm 0.20) 1.80 \pm 0.10$
29.04-03.05.2007	120	E	4.85	0.4	0.434	2.6	1.37 ± 0.20

[a]Detailed analysis is given in [11].
[b]There is an indication of another time scale of 0.4 days in the data.
[c]There were not enough measurements to calculate a reliable time scale.
[d]Due to human error, slightly different frequency setup was used than previously.

Table 1: Summary of the IDV observations of J1128+592. The table lists the observing dates (Col. 1), the day of the year corresponding to middle of the observing epoch (Col. 2), the observing radio telescopes (Col. 3, 'E' for Effelsberg, 'U' for Urumqi), the frequency of the observation (Col. 4), the average modulation index of the calibrators (m_0, Col. 5), the average flux density of J1128+592 (Col. 6) the modulation index of J1128+592 (Col. 7) and the derived characteristic variability time scale (Col. 8) in days.

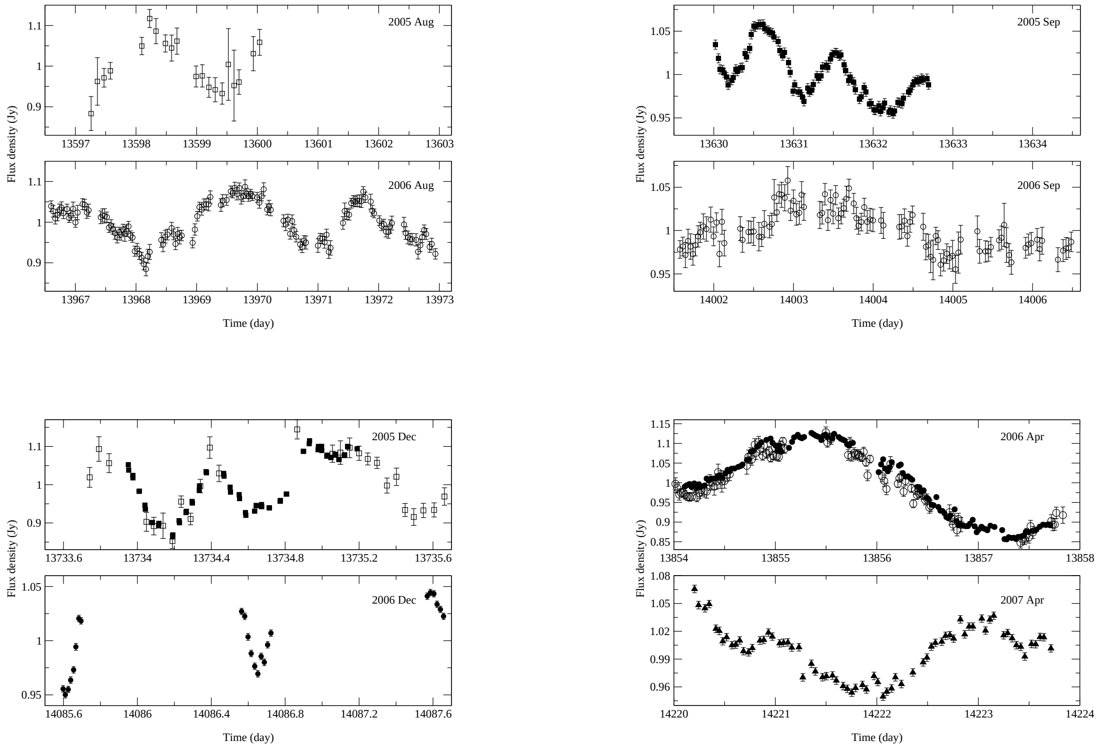

Figure 1: The 4.85 GHz light-curves of J1128+592 from 8 epochs. The twin plots show observational epochs which separated by approximately one year. Open symbols represent Urumqi observations, filled symbols represent Effelsberg observations.The abscissas display the date (the format is J.D.-2440000.0). The ordinates show the normalised flux density.

the dashed line in Fig. 2. For the 2007 April 20-23 epoch we used the longer time-scale value in the model-fitting. Using the smaller time-scale value did not change the resulting fit profoundly: the $\chi^2_{\rm r}$ value of the fit became 8.5.

In the anisotropic model, the scintillation time scale also depends on the ellipticity of the scintillation pattern and on the direction in which the relative velocity vector (between the Earth and the screen) "cuts through" the elliptical scintillation pattern. Thus, the fitted parameters obtained from the anisotropic scintillation model are the velocity components of the scattering screen, the scattering length-scale (which depends on the screen distance and the scattering angle), the angular ratio of the anisotropy and its position angle. The obtained parameters are tabulated in Table 2 together with the $\chi^2_{\rm r}$ value of the fit.

Apart from the similarities in the light curves in Fig. 1, there is also a clear difference: the variations in 2006 December and 2007 April are much more reduced than those in the earlier epochs. The continuous decrease of the **variability index during 2007** is also clear from Table 1. An annual modulation model cannot give account for the changes in the value of Y. This can be caused either by changes in the scattering plasma or by changes in the source itself. The mean flux density at 4.85 GHz changed significantly during the ~ 2.5 years of monitoring of J1128+592. The flux density increased by $\sim 27\,\%$ until 2006 February, then monotonously decreased until our last

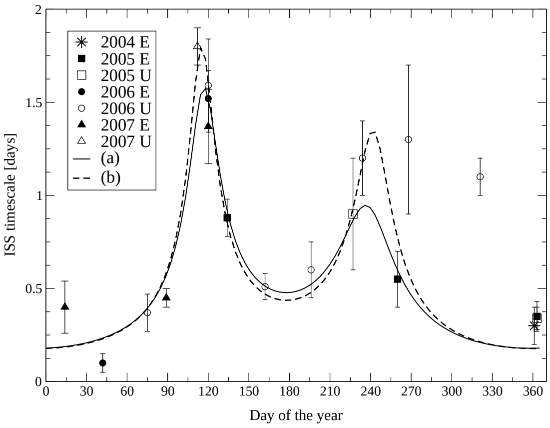

Figure 2: The IDV time scale of J1128+592 measured at 4.85 GHz plotted versus day of the year and fitted by two different anisotropic annual modulation models. Different symbols represent observations performed in different years: stars stands for 2004, squares for 2005, circles for 2006 and triangles for 2007. Filled symbols represent observations carried out with the Effelsberg telescope, open symbols for observations with the Urumqi telescope.

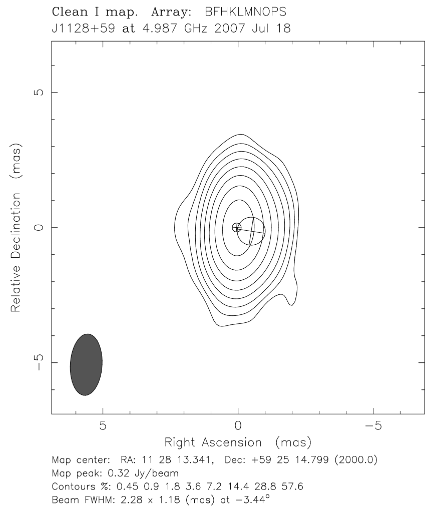

Figure 3: VLBA model-fit of J1128+592 at 5 GHz. Observation took place on **18th** of July 2007. The restoring beam is displayed at the lower left side of the map.

	v_{RA} $(\mathrm{km\ s^{-1}})$	v_{δ} $(\mathrm{km\ s^{-1}})$	s_0 $10^5\,(\mathrm{km})$	r	$90^\circ-\gamma$ $(^\circ)$	χ^2_r
(a)	-3.1 ± 7.8	-11.5 ± 1.9	11.8 ± 2.5	4.2 ± 2.0	-88.6 ± 5.7	3.0
(b)	-0.6 ± 8.3	-10.8 ± 1.6	13.4 ± 2.8	5.8 ± 2.7	-89.4 ± 5.0	8.4

Table 2: Fit parameters of the annual modulation models shown in Fig. 2. Col. 1 shows labels used for the different fit curves . Col. 2 and 3 give the velocity components of the screen in Right Ascension and Declination direction. Col. 4 shows the scintillation length scale, Col. 5 the axial **ratio** and Col. 6 the position angle of the scintillation pattern. In Col. 7, we give the reduced χ^2_r of the fit.

observation. This long term flux density change suggests a source-intrinsic origin (e.g. an ejection of a new jet component), which could influence the variability behaviour of the source on IDV time scales as well. (This effect might be responsible for the slower variability in 2006 September compared to the variations a year before, Fig. 1).

4. VLBA observations

We proposed multi-epoch and multi-frequency VLBA observations of J1128+592 in order to reveal any intrinsic change in the source. We will have six epochs of VLBA observations of J1128+592 separated by 6 to 8 weeks, performed quasi-simultaneously at 5 GHz, 8 GHz and 15 GHz. The first observation was carried out on 18th of July.

After correlation with the VLBA correlator in Socorro, *a priori* amplitude calibration using system temperature measurement and fringe-fitting were carried out with the standard AIPS procedures. Editing, phase and amplitude self-calibration and imaging were carried out using the Caltech Difmap package.

Preliminary results of fitting the visibility data with circular Gaussian components indicate that the 5 GHz data can be described by 2 circular Gaussian components (shown in Fig. 3); the second feature is at a position angle of $\approx -95^\circ$ from the core. Gaussian model-fit to the 8 GHz visibilities yields a very similar position angle as well. These values are very similar to the position angles derived from the anisotropic annual modulation scenario, which might suggest that the anisotropy **in the scattering model may be related to the orientation** of the source structure.

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