High resolution studies of the IDV quasar J1128+592

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Abstract. J1128+592 is a compact radio quasar and, as ~ 30% of flat spectrum radio sources, shows fast variations in the cm-wavelength regime on time-scales of an hour to few days. Such phenomenon is often explained by scattering of radio waves in the turbulent, ionized interstellar matter of the Milky Way. Regular monitoring observations of J1128+592 performed by the Effelsberg 100-meter and the Urumqi 25-meter radio telescope during the last four years confirmed this, since a seasonal cycle of the variability time-scale was revealed. This effect is one of the most convincing argument in favor of the interstellar scattering induced fast radio variations in blazars. Multi-epoch, multi-frequency observations made by the Very Long Baseline Array (VLBA) together with the annual modulation model enabled us to determine a lower limit of the distance of the screen responsible for the rapid variability. Additionally, it revealed source-intrinsic-change, which affected the variability pattern.

1. Introduction
Intraday Variability (IDV, Witzel et al. 1986) is a common phenomenon in flat spectrum radio sources, with a fraction of 20-40% showing this effect. The typical time-scales of the variations range from about 20 minutes to a few days. If the variations originated from the source itself, using causality and the common light-travel time arguments, these short time-scales would invoke extremely small source sizes (in range of µas) and consequently very high brightness temperatures. Brightness temperature values in excess of the inverse-Compton limit (10^{12} K, Kellermann and Pauliny-Toth 1969) are usually explained via relativistic beaming. However, in the case of IDV sources, the invoked Doppler factors are much higher than those derived from different observing methods such as kinetic studies of features in the highly relativistic jets of blazars.

The solution to this controversy is the source-extrinsic theory of IDV (e.g., Rickett 2001 and references therein). This explains that the rapid variations are caused during the propagation of radio waves thus, they do not originate from the source itself. The variations are caused by interstellar scintillation (ISS) in the turbulent, ionized interstellar medium of the Milky Way.

One of the most convincing argument in favor of this propagation theory is the so-called “annual modulation” of the variability time-scale. In the source-extrinsic scenario, the characteristic variability time-scale is inversely proportional to the relative velocity between the observer and the scattering medium. The annual modulation of the variability time-scale
Figure 1. The IDV time-scale of J1128+592 measured at 5 GHz plotted versus day of the year (DOY). Different symbols represent observations performed in different years: star stands for 2004, squares for 2005, circles for 2006, diamonds for 2007, triangles for 2008 and down-triangles for 2009. Filled symbols represent observations performed with the Effelsberg telescope, open symbols for observations with the Urumqi telescope. Line represents the fit of annual modulation model.

Figure 2. 5 GHz (top) and 15 GHz (bottom) VLBA maps of J1128+592 from epoch 2007.661. The unit of the axes is milli-arcsecond. The peak flux intensities are 299 mJy/beam and 229 mJy/beam at 5 GHz and 15 GHz, respectively. The lowest positive contours are 1 mJy/beam. Contours increase by a factor of two. The beam sizes are shown on the bottom left corners of the images.

reflects the systematic variation in the relative velocity vector between the orbiting Earth (the observer) and the moving scattering screen. Such annual cycle was identified in several IDV sources (e.g., J1819+3845, Dennett-Thrope and de Bruyn 2003, PKS 1622-253 Carter et al. 2009 and references therein).

2. Annual modulation
J1128+592 is an IDV source. During the last four years, the source was regularly observed in more than 30 densely time-sampled flux-density monitoring observations with the Effelsberg 100-meter (MPIfR, Germany) and the Urumqi 25-meter (China) radio telescopes at 5 GHz. (Last observation was carried out in November 2009.) Part of these observations were summarized in previous papers (Gabányi et al. 2007, and references therein). Regarding the observational techniques and data reduction steps we refer to those papers, as well as Fuhrmann et al. (2008) and Marchili (2009).

In most of these observations, J1128+592 showed pronounced variability with peak-to-trough amplitudes exceeding 10 %. The measured characteristic variability time-scales differ significantly from epoch to epoch, ranging from 0.2 to 1.6 days. The different IDV time-scales of J1128+592 measured at different times of the year are indicative of an annual cycle. In the ISS model, the seasonal cycle of the characteristic variability time-scale can be explained as a pure geometrical effect. The scattering material is regarded to be located in a thin plasma screen at
some distance from the Earth. The IDV time-scale depends on the relative velocity between the observer and the screen. When the relative velocity is the lowest (the screen and the Earth move approximately parallel), the longest is the IDV time-scale, thus slow variations can be observed. Half year later, when the Earth, due to its orbital motion, moves the opposite direction (thus anti-parallel with the screen), the relative velocity becomes the largest, the observed IDV time-scale is the shortest, thus fast variations can be observed.

In a more general scenario, the scintillation pattern is assumed to be anisotropic. Then the variability time-scale also depends on the ellipticity of the scintillation pattern and the direction in which the relative velocity vector “cuts through” the elliptical scintillation pattern (and not just the absolute value of the velocity vector). The form of the anisotropic annual modulation model (Bignall et al. 2006) which was fitted to the IDV time-scales of J1128+592 is the following: 

$$t(T) = \frac{s\sqrt{r^2 + (r^2 - 1)(v(T) \cdot S)^2}}{\sqrt{(v(T))^2 + (r^2 - 1)(v(T) \cdot S)^2}}$$

where $s$ is the scintillation length-scale (the product of the angular size of the scintillating source and the screen distance), $v(T)$ is the relative velocity between the scintillation screen and the observer, $r$ denotes the axial ratio of the anisotropy. When fitting the model, we derive the velocity of the scattering screen in Right Ascension ($v_{RA}$) and in Declination ($v_\delta$) direction.

The best fit model to all to observations made so far is shown in Fig. 1. The parameters of the fit: $v_{RA} = 1 \pm 4$ km/s, $v_\delta = -11 \pm 2$ km/s, $s = (12 \pm 1) \cdot 10^5$ km, $r = 3.0 \pm 0.8$, $\beta = -94^\circ \pm 5^\circ$. ($\beta$ is measured North through East).

Most of these values are similar to those obtained for other IDV sources showing annual modulation (e.g. J1819+3845, Dennett-Thrope and de Bruyn 2003), however the axial ratios are larger than 4. For example in the case of PKS 1257-326 (Bignall et al. 2006), the axial ratio is $\sim 12$. Walker et al. (2009) studied whether even higher anisotropy values can give better fits to the measured time-scales in the case of J1819+3845 and PKS 1257-326. They found that the anisotropy can be so large in these two sources that the scintillation pattern can be more effectively described as one dimensional. Therefore, they concluded it would be more likely that the anisotropy is caused by the scattering material rather than the source intrinsic structure. In the case of J1128+592, the axial ratio is not large enough to dismiss the possibility that the anisotropy, observed in the annual modulation, is caused by the source-intrinsic structure.

3. Very Long Baseline Array observations

Between July 2007 and February 2008, six epochs of Very Long Baseline Array (VLBA) observations of J1128+592 were performed. The measurements were carried out at three frequencies: at 5 GHz, 8 GHz and 15 GHz. After correlation at the VLBA correlator in Socorro (NRAO), the data were calibrated and fringe-fitted using the standard procedures within the AIPS (Astronomical Image Processing System) software package. The post-processing of the data included the usual steps of editing, phase- and amplitude self-calibration, and imaging. The Caltech DIFMAP package was used to perform these task and to fit the uv-data. We fitted the source structure in every epoch with circular Gaussian components. More details on the data reduction are given in Gabányi et al. (2009).

These observations revealed that the source has an approximately east-west oriented core-jet structure (Fig. 2). The position angle of the jet component is $\sim -116^\circ$ at 5 GHz, which is remarkably similar to the orientation derived from the annual modulation model of the IDV time-scale. This may indicate that the anisotropy in the scintillation pattern is caused by the source structure rather than the intervening turbulent ISM. However, additional observations are required to clarify unambiguously the roles of the scattering plasma and source structure in the anisotropic scattering. According to Rickett et al. (2002), a negative “overshoot” in the
light-curve auto-correlation is indicative of anisotropy caused by the scattering medium.

From the VLBA measurements, we derived an upper limit for the scintillating source size at 5 GHz: \(0.2 \pm 0.05\) mas. Using this, and the scintillation length-scale provided by the annual modulation model, we can derive a lower limit for the distance of the ISM screen responsible for the IDV: \(\sim 30\) pc. This is three times larger than the values derived for the much faster varying J1819+3845 (Denett-Thrope and de Bruyn 2003) and PKS1257-326 (Bignall et al., 2006). However, it still places the scattering screen within the Local Bubble.

We collected and (re-)analyzed six epochs of archival VLBA observations of J1128+592 made at 5 GHz during 2004. We fitted the source with Gaussian components in order to derive the size of the core. The average core size from 2004 is \(\sim 0.07 \pm 0.02\) mas, which is less than half of the value we measured in our VLBA observations in 2007 and 2008.

Our IDV monitoring observations indicated that the variability-strength of the source has declined monotonously since 2006. Additionally, the source underwent a flare-like event, its flux density increased until 2006, then decreased by \(\sim 50\%\) until late 2007. The strength of variability is usually described by the modulation index \((m)\), which is the ratio of the standard deviation of the flux density to the average flux density. According to the ISS theory of IDV (e.g., Walker 1998), the modulation index goes as \(m \sim \theta^{-7/6}\), where \(\theta\) is the source size. In the case of J1128+592, the modulation index was measured to be around \(3 \sim 4\%\) at the time we had the VLBA observations. Using this equation, we would expect that the source had a modulation index at least \(10\%\) during 2004. Unfortunately, our first single dish observation of the source was made in late December 2004, however the modulation index of J1128+592 was mostly between 7\% and 10\% during 2005. This indicates that the weakening of the strength of IDV can be explained by the combination of the expansion of the VLBI core (or the dominant scintillating component hidden inside) and the decreasing flux density.

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