Serendipitous VLBI detection of rapid, large-amplitude, intraday variability in QSO 1156+295

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ABSTRACT

Aims. We report a serendipitous detection of rapid, large amplitude flux density variations in the highly core-dominated, flat-spectrum radio quasar 1156+295 during an observing session at the Very Long Baseline Array (VLBA).

Methods. The source was observed as a part of the MOJAVE survey programme with the VLBA at 15 GHz on February 5, 2007. Large amplitude variability in the correlated flux density, unexplainable in terms of the source structure, was first discovered while processing the data, and later confirmed by calibrating the antenna gains using 24 other sources observed in the experiment.

Results. The source shows variations in the correlated flux density as high as 40% on a timescale of only 2.7 hours. This places 1156+295 between the classical IDV sources and the so-called intra-hour variables. The observed variability timescale and the modulation index of 13% are consistent with interstellar scintillation by a nearby, highly turbulent scattering screen. The large modulation index at 15 GHz implies a scattering measure that is atypically high for a high galactic latitude source such as 1156+295.

Key words. Galaxies: active – Galaxies: jets – quasars: individual: 1156+295 – Techniques: interferometric

1. Introduction

Intraday variability (IDV) of compact, radio-loud AGN at cm-wavelengths was first discovered in the mid-1980s (Witzel et al. 1986; Heeschen et al. 1987) and both source-intrinsic and extrinsic mechanisms for IDV have been vigorously studied (for a review, see e.g. Wagner & Witzel 1995). Detection of time delays in the variability pattern arrival times between widely separated telescopes, as well as observed annual modulation of the variability timescale, have shown conclusively that interstellar scintillation (ISS) is the cause of intra-hour flux density variations observed in the three most extreme IDV sources PKS 0405-385 (Jauncey et al. 2000), J1819+3845 (Dennett-Thorpe & de Bruyn 2002, 2003), and PKS 1257-326 (Bignall et al. 2003, 2006). Evidence for the ISS origin of IDV was found also in the cases of 0917+624 (Rickett et al. 2001; Jauncey & Macquart 2001; Fuhrmann et al. 2002), PKS 1519-273 (Jauncey et al. 2003), and J1128+5925 (Gabányi et al. 2007). This provided the possibility to study both small-scale spatial fluctuations in the interstellar medium and the structure of compact radio sources on the microarcsecond scale. Unfortunately, the extreme IDV sources, which are the most suitable for these studies, are rare. By “extreme”, we mean sources showing variability on timescales of a few hours or less and with an rms amplitude of modulation of over 10%. In this Letter, we report the serendipitous discovery of very large amplitude IDV in quasar 1156+295 with a timescale of variations shorter than 3 h. This discovery is also unusual because it was achieved by a VLBI experiment.

1156+295 (4C 29.45) is an optically violently variable quasar at z = 0.729 (Burbidge 1968), which has Galactic coordinates $l = 199.4^\circ$, $b = +78.4^\circ$. The source is strongly variable throughout the electromagnetic spectrum from radio to gamma-rays. At radio frequencies, 1156+295 shows significant long-term variability on a timescale of months (e.g. Kovalev et al. 2002). Wills et al. (1983) reported a range of at least 5 magnitudes in the optical brightness, and in gamma-rays Sreekumar et al. (1996) detected an order of magnitude variability using the EGRET

Fig. 1. Naturally weighted 15 GHz VLBA image of 1156+295 observed on February 5, 2007. The map peak brightness is 1.46 Jy beam$^{-1}$. The contours begin at 0.7 mJy beam$^{-1}$ and increase in steps of 2. Since the source flux density varied significantly during the observation, an amplitude self-calibration had to be used early in the imaging process. This may affect the image quality.
instrument onboard the Compton Gamma Ray Observatory. During high radio brightness states, 1156+295 appears to be highly core-dominated in VLBI images (95% at some epochs (Kovalev et al. 2005); see also Fig. 1). Supernovaluminous motion at speeds ranging from 3.5\,h^{-1}c to 14.1\,h^{-1}c were reported by e.g. Piner & Kingham (1997), Jorstad et al. (2001), (Hong et al. 2004), and Kellermann et al. (2004).

In the optical bands, 1156+295 shows rapid variations on timescales of between less than 30 minutes and 3 days (Wills et al. 1983; Raiteri et al. 1998). The first IDV detection of 1156+295 at radio frequencies was reported by Lovell et al. (2003), who observed the source with the VLA at 5 GHz in January 2002. Their study measured rms flux density variations of 167\,mJy during 3 nights of observations and a variability timescale of $\sim 24\,h$. The relative amplitude of variations observed by Lovell et al. (2003) was far smaller than reported here.

Throughout this paper, we use the following cosmological parameters: $H_0 = 73\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$. The angular scaling conversion for $z = 0.729$ is 7.07 pc mas$^{-1}$.

2. Observations and analysis

Quasar 1156+295 and 24 other compact radio sources were observed with the NRAO’s Very Long Baseline Array (VLBA) at 15 GHz as a part of the MOJAVE project (Lister & Homan 2005) on February 5, 2007. The entire observing session had a duration of 24 hours, which included 9 scans of 1156+295, each lasting 4.7 minutes. The signal was recorded in dual-polarisation mode: 4 IFs (each with 8 MHz bandwidth) per circular polarisation and 1-bit sampling. The data from the experiment were calibrated following standard procedures of VLBI data reduction (see e.g. Lister & Homan 2005). After a priori ampli-

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1 We note that 1156+295 was observed several times in the MOJAVE survey and its IDV behaviour during the rest of the MOJAVE epochs will be analysed in Kuchibhotla et al. (in prep.).
Calibrated correlated Stokes I flux density of 1156+295 (in Jy) as a function of $(u,v)$ radius (in M\(_\odot\)) for each individual scan of the VLBI experiment on February 5, 2007. The data has been averaged over the IFs and for 30 s in time. The different scans are shown in different colours with the scan start time in UT indicated in the legend.

Fig. 3.

Integrated flux density curve of 1156+295, obtained by averaging the correlated flux density at projected baselines shorter than 100 M\(_\odot\). The error bars represent the standard deviation of the correlated flux density (at baselines < 100 M\(_\odot\)) in each scan. Colour coding of the scans is the same as in Fig. 3.

The two important quantities in the analysis of IDV are the modulation index and the characteristic timescale of variability. We consider the average of the peak-to-trough and trough-to-peak times of the large dip to be the timescale of variability, which is therefore \( t_{\text{var}} = 2.7 \pm 0.5 \text{ h} \). We note that our \( t_{\text{var}} \) is approximately a factor of 1.7 times longer than the timescale on which the autocorrelation function of intensity fluctuations reaches a fraction 1/e of its maximum value [Jauneys & Macquarta (2001)]. The modulation index \( m \), defined to be the standard deviation of the source flux density divided by the mean source flux density, is \( 13 \pm 3 \% \) for the flux density curve in Fig. 4. The uncertainties in \( t_{\text{var}} \) and \( m \) were estimated following the analysis in Dennett-Thorpe & de Bruyn (2003).

3. Discussion

If we assumed a source-intrinsic origin of the observed variability in 1156+295, it would imply, by light travel time arguments, a brightness temperature of \( \gtrsim 2 \times 10^{10} \text{ K} \), which is far in excess of the inverse Compton (IC) limit of \( 10^{12} \text{ K} \) [Kellermann & Pauliny-Toth (1969)]. A Doppler factor higher than \( \sim 270 \) would then be required to avoid the IC catastrophe. This would cause severe problems with the energy requirements in the source [Begelman et al. (1994)]. Extremely fast jets are also unlikely in the light of VLBI monitoring surveys, which indicate that the maximum jet Lorentz factor \( \Gamma \) is 30 – 40 [Cohen et al. (2007)]. The standard model of incoherent synchrotron radiation from relativistic electrons in the jet would therefore have significant difficulties in explaining the observed variability, if it were intrinsic. For this reason, we concentrate on two possible extrinsic causes: interstellar scintillation and an extreme scattering event.

Propagation effects in the ionised medium of the Milky Way will cause a sufficiently compact source to scintillate (for review of ISS, see e.g. Rickett (1990), Goodman (1997). Since the observed \( m \) in 1156+295 is clearly below 100\%, it is reasonable...
to assume that refractive scintillation is fully quenched and to consider only refractive ISS. The observed r_{var} and m constrain the properties of a possible scinttering screen and the size of the scintillating source. Because of the high m in our case, it appears likely that our observing frequency is close to the critical frequency ν_c between strong and weak scattering regimes. Goodman (1997) provided a formula for m that can be used to interpolate solutions close to ν_c, where the asymptotic solutions for strong and weak regimes break down. Combining his Eqs. 10, 12, 18, 19, and 20, and assuming a Gaussian brightness profile for the source, we calculated the screen distance, D_{scr}, and the FWHM size of the scintillating source $\theta_s^{FWHM}$ as a function of scattering measure $SM = \int C_s^2 dx$, where $C_s^2$ is the strength of the electron-density fluctuations\(^2\) (Fig. 5). The results were parameterised by the screen velocity. We estimated the uncertainties in $D_{scr}$ and $\theta_s^{FWHM}$ by Monte Carlo methods and the hatched regions in Fig. 5 show the 1σ error for these quantities. In addition, the results given by the interpolation formula of Goodman (1997) were confirmed by numerically integrating the intensity covariance function for refractive scintillation (see Appendix A in Rickett et al. 2006). In the bottom panel of Fig. 5, we indicate an approximate lower limit to the source size, $\theta_s^{FWHM} \geq 17\mu$as, given by the IC catastrophe limit and by assuming an upper limit of 50 for the Doppler factor (Lahteenmäki & Valtaoja 1999, Cohen et al. 2007). As can be seen from Fig. 5 if the variability is due to ISS, we have either a rather nearby screen ($D_{scr} \leq 300$ pc) with $SM \geq 0.5$ m\(^2\) pc or $\theta_s^{FWHM}$ so small that it would require Doppler factor exceeding 50.

We can estimate $\theta_s^{FWHM}$ independently by assuming that there is appropriate equipartition between the energy densities of the magnetic field and the radiating electrons (Scott & Readhead 1977). We assume the synchrotron peak frequency to be 15 GHz and the corresponding peak flux density to be 1.5 Jy. This is based on the assumption that the scintillating component is the core of a Blandford & Königl (1979) jet type and corresponds to the $\tau = 1$ surface at our observing frequency. The resulting equipartition size is $\theta_s^{FWHM} \sim 270 \cdot \delta^{-1/2}$ $\mu$as, where $\delta$ is the Doppler factor. If we again take $\delta \leq 50$, this results in $\theta_s^{FWHM} \approx 55\mu$as, $SM \approx 4$ m\(^2\) pc, and $D_{scr} \leq 100$ pc for screen velocities between 10 and 50 km s\(^{-1}\). Since the Galactic electron distribution model by Cordes & Lazio (2002) predicts a scattering measure of only 0.1 m\(^2\) pc\(^{-1}\) for the line-of-sight towards 1156+295, our results indicate a nearby, localised region of highly turbulent ionised gas in that direction.

The frequency-dependence of m is slightly surprising: one would not expect m to increase from 5.8% at 5 GHz (Lovell et al. 2003) to 13% at 15 GHz, unless the scattering is strong and the source is smaller than the scattering angle. In that case the scintillating component would contain only about 30 – 50% of the total flux density of the core, because otherwise the observed m would be significantly higher. Another possibility is that 1156+295 was in a more compact stage during our observation than it was 5 years earlier. Simultaneous multi-frequency measurements of m are required to clarify this.

It is also possible that the observed variations are not due to standard ISS, but instead correspond to an isolated extreme scattering event (ESE; Fiedler et al. 1987). Unfortunately, our short, single-frequency observation does not provide us with sufficient information to distinguish between these two cases. However, the shape of the flux density curve resembles an ESE with two maxima symmetrically surrounding a deep minimum.

\(^2\) Note that $\theta_s$ in Goodman (1997) is approximately $\theta_s^{FWHM}/2.35$. 

**Fig. 5.** Parameters of the possible scattering screen. Top: The distance to the screen as a function of the scattering measure SM. Different screen velocities are shown in different colours. Bottom: The scintillating source size as a function of SM. The right edge of the panel gives the Doppler factor if $\theta_s^{FWHM}$ is equal to equipartition size. The grey shaded area corresponds to $\theta_s^{FWHM} < 17\mu$as. In both panels, the hatched region around the solid lines gives 1σ error for the plotted quantities. The +1σ lines in the $\theta_s^{FWHM}$ plot roughly correspond to -1σ lines in the $D_{scr}$ plot and vice versa.

Although “classical” ESEs have durations of between weeks and months, Cimö et al. (2002) reported an event in 0954+658 with a duration of less than 2 days. The extremely short timescale of our event would, in the case of an ESE, imply a cloud size < 0.01 AU.

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