Recent WSRT Results on Two Prototypical Compact AGN: BL Lac and J1819+3845

A.G. de Bruyn[*]

ASTRON, Dwingeloo & Kapteyn Astronomical Institute, University of Groningen
E-mail: ger@astron.nl

Recent WSRT observations at 21 cm and 85 cm of the radio source BLLac, long known for its rapid variations and strong linear polarization, has revealed a strong increase in its 21 cm polarization. We also detect polarization at 85 cm. The rotation measure (RM) of the source varies with wavelength and may even vary slightly with time. The Galactic foreground contribution to the observed RM is estimated to be about – 200 rad m^{-2}, close to the observed values at 21 cm and 85 cm. This implies that the contribution intrinsic to the jet is rather small. We present a simple model with multiple polarized features in the jet to explain the broadband 85 cm Faraday spectra. Low frequency polarimetry using RM synthesis is a very sensitive probe of the magneto-ionic medium close the core of an AGN. The VLBI resolution at these frequencies is insufficient to discern the various structures.

The scintillating compact intra hour variable (IHV) quasar J1819+3845, discovered in Jan 1999, suddenly stopped scintillating sometime in 2006/2007. We present a 13-year lightcurve, based largely on WSRT multi-frequency data. Following a slow outburst in the period 2000-2006 the source luminosity is now again slowly declining. The source is barely resolved with VLBI arrays and maintains a slightly inverted radio spectrum.. An analysis of the linear polarization data in the period 2000-2006 reveals systematic time delays attributed to the separation between a total intensity 'core' and slowly moving polarized features in the jet. Various independent methods yield a distance of the scattering medium of only 1–2 parsecs. The screen responsible for the scintillation is extremely small ($\approx$100 AU) and has a sharp (< 6AU) edge. The plasma density is very high and the screen is highly overpressured relative to the surrounding medium. For an extensive account of the large body of data on J1819+3845, and an analysis of the properties of both quasar and screen, we refer to [1].

---

[*]Speaker.

1. BL Lac: 21 cm and 85 cm polarimetry

The radio source BL Lac, namegiver for its class, is known for its rapid radio variability and strong linear polarization at cm wavelengths. Its outbursts follow the classic behaviour of outbursts at high frequencies followed by fairly rapid intensity decay. High frequency VLBA polarimetry reveals considerable and probably time variable RM structure near the core (see [2, 3, 4, 5]). Most of the high frequency polarized emission originates in a region 1–2 mas from the core. At 21 cm the source show a 40 mas jet towards the south in 1995 [2]. The source is surrounded by a faint radio halo, about 10" in size, with a 6 cm flux density of a few mJy [6].

Here we report on new WSRT observations in the 1300-1460 MHz and 315-385 MHz bands in the years 2010 through 2012. BL Lac is often used as a 21 cm polarization calibrator for the WSRT and following the discovery of a significant increase in the 21 cm polarization in September 2010 we acquired several more observations. The calibration of the data was done using standard procedures. Because of the large RM of BL Lac, about –200 rad m^{-2} we decided to analyze the data with both traditional λ^2-fitting and RM-synthesis methods (see [7]). In Fig. 1 we show the two methods side by side. Although the 160 MHz band centered at 1380 MHz creates an RMSF of about 350 rad m^{-2} width, the RM value, if assumed to be due to a single component, can be determined to great accuracy: –205 ± 0.1 rad m^{-2} at 21 cm. The formal error in this value is smaller than the uncertainty due to the contribution of the ionosphere.
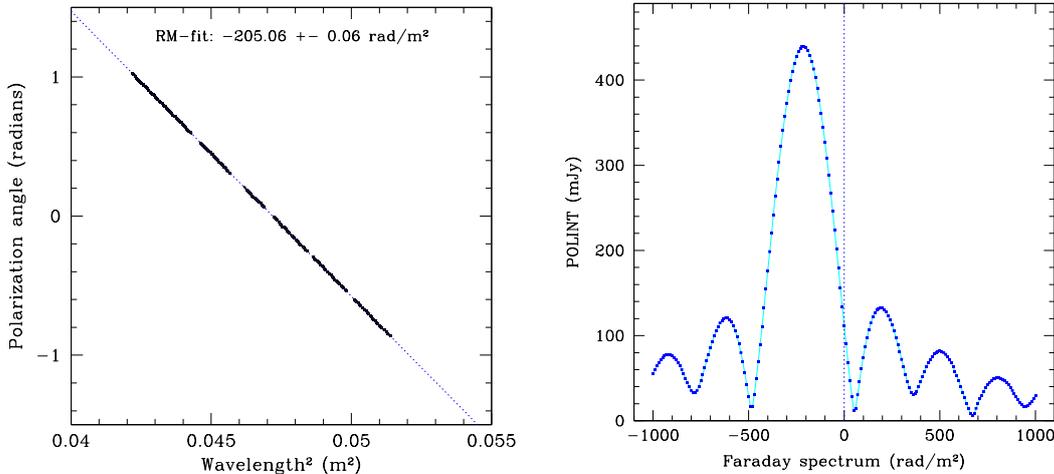
Figure 1: Traditional λ^2-fitting (**left**) and RM synthesis presentations (**right**) of BL Lac 's 21 cm linear polarization on 1 April 2012. The total flux density of BL Lac at 21 cm is 3.8 Jy at this epoch.

The polarization percentage of BL Lac at 85 cm is much smaller than at 21 cm (50 mJy on a total intensity of 2.6 Jy) and standard λ^2-fitting approaches will not work on noisy spectral data. One then has to recourse to an RM synthesis analysis. In Fig. 2 we show the Faraday spectrum of BL Lac at 85 cm on 2 April 2012. The peak value is located at –211 rad m^{-2}, which is slightly, but significantly, different from that at 21 cm. In Fig. 2 we show the observed RM values of polarized radio sources in an 8 degree area around BL Lac. There is a large scatter in the field RM's around

BL Lac (which is at a Galactic latitude of -10 degree) with a median value of about –200 rad m^{-2}. This was also the original value assumed by [3] and earlier studies; they, however, argued that the Galactic contribution was more likely to be closer to –100 rad m^{-2}. Based on the data in Fig. 2 we, again, assume –200 rad m^{-2} for the Galactic contribution. The RM intrinsic to BL Lac would then be less than about 10–20 rad m^{-2}. If we perform a separate RM synthesis of the polarization signals within seven adjacent 10 MHz bands at 85 cm we find significant variations in the polarization percentage as a function of frequency; the RM values themselves remain the same to within the errors. The polarization percentages also differ on the two epochs. These results are plotted in the left part of Fig. 3. The fact that the polarization percentage **increases** with frequency could be due to two components in the jet with a slightly different RM. A fit-by-eye to the fractional polarization percentage as a function of wavelength squared suggests that a simple Burn-slab model with a Faraday depth of 5 rad m^{-2} could explain the data. In the right side of Fig. 3 we show a toy model for the polarization structure in the jet of BL Lac. It shows two possible configurations that could explain the behaviour in the 85 cm band: two Faraday-thin components with values RM$_1$ and RM$_2$ or a single Faraday feature that is becoming Faraday thick. However, this is only one of many possible interpretations.
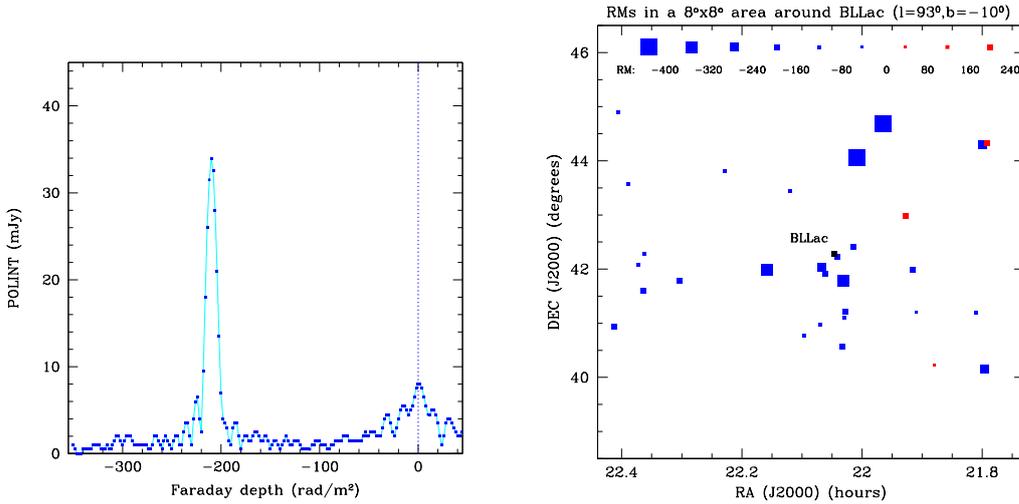
Figure 2: Left: Faraday spectrum of BL Lac at 85 cm on 2 April 2012. The emission from BL Lac peaks at an RM = –211 rad m^{-2}. The emission near an RM $\approx$ 0 rad m^{-2} is due to instrumental polarization leakage. **Right:** Map of the rotation measures of sources around BL Lac, which is indicated by a black dot. Most points are from the NVSS catalog of [8]. Some of the values very close to BL Lac are from our own 85 cm data.

It is likely that the polarization at low frequencies originates in the inner jet, close to the core from where the high frequency polarization is emitted. On the basis of the VLBA 1.4 GHz total intensity image taken in 1995 [2] we estimate that the jet only has enough surface brightness to explain a (maximally 70%) polarized feature of 400 mJy at 21 cm if we come to within 5 mas from the core. It is of course possible that the outer jet brightened significantly in the intervening 17 years. However, there is no evidence for a substantial flux increase in the total 21 cm flux density of BLLac in the last few years. Only the polarization percentage has nearly doubled in 2

years. High resolution 21 cm and shorter wavelength polarization VLBI imaging is required to find out what has happened and indicate whether the jet polarization structure has changed or that the surrounding or internal Faraday fog [4] has changed its morphology. In view of the complicated RM structure near the core one might cast doubt on some of the RM's determined from just 2 or 3 wavelength points.
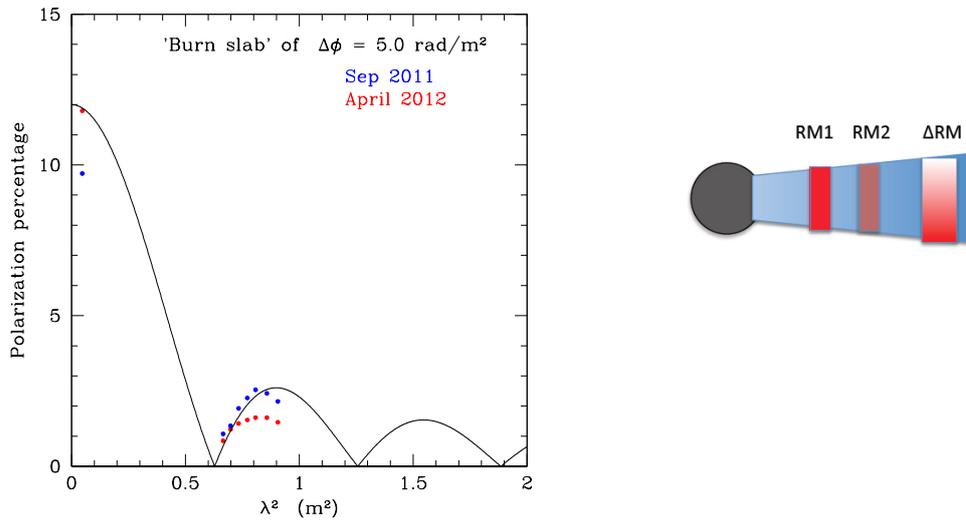
Figure 3: Left: Fractional polarization percentage of BLLac as a function of wavelength squared. Observations in Sep 2011 and April 2012 are shown. The continuous curve shows the expected behaviour for a source consisting of a 'Burn-slab' of magneto-ionic medium with a Faraday depth of 5 rad m^{-2}. **Right**: Cartoon of two possible models for the long wavelength Faraday properties of the jet of BL Lac

2. J1819+3845: long term evolution and jet structure of an IHV source

The quasar J1819+3845 (once) was the most dramatically extragalactic variable radio source. It was discovered in 1999 [9]. These variations were shown to be due to scintillations caused by a local turbulent plasma screen [10]. A large amount of WSRT data at 6 cm and 21 cm wavelength has been previously presented [11, 12, 13]. In Fig. 4 we show the intensity variations, simultaneously at 3 wavelengths, on 1 April 2002. The scintillations on this date reached a record flux density of 780 mJy, more than 2.5 times the intrinsic source flux at the time. It is possible, in fact, that the source was temporarily somewhat brighter on this day. Besides this epoch we have not seen any evidence for rapid intrinsic variations in the source flux density. The long term trend of the variations at 6 cm are shown in Fig. 4. The character of the scintillation-induced variations did not change much in the first 7 years. The cessation of variability in the source occurred sometime between June 2006 and Feb 2007 [14], a timespan less than 9 months. There was no indication in the source behaviour that this was going to occur as is clear from the 'swan song' of J1819+3845 in the final 7 months of dense monitoring shown in Fig. 6. From 2007 onwards the source became a very slowly evolving boring source (see also [15]). There are two possible causes for the cessation of the scintillations:

the screen moved out of the way or the source expanded. Let us first discuss the latter possibility. VLBI observation of J1819+3845 were made at 8.4 GHz and higher frequencies in June 2003 and Jan 2006 [16]. They showed J1819+3845 to be an unremarkable largely unresolved source ($<$ 1 mas). VLBA observations at 8.4 GHz reported by [17], taken **after** the source stopped scintillating still show an unresolved source. In the weak scintillation regime [18] it would require an extraordinarily rapid expansion, by more than an order of magnitude in 9 months, of the whole source to explain the dramatic drop in modulation index shown in Fig.4. For further discussion on this we refer to [1].

We are thus led to conclude that the cessation of the scintillations is due to J1819+3845 emerging from behind the screen. The edge of the screen must be sharper than about 6 AU. The total extent of the screen, given the minimum period of 7.5 years scintillations, is at least 50 AU.
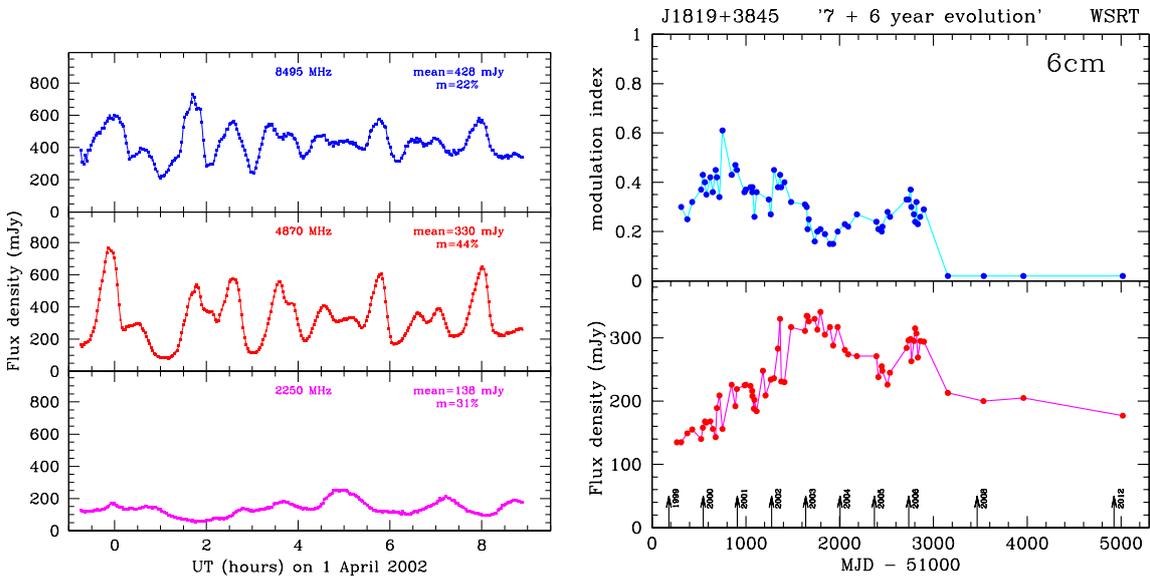
Figure 4: Left: Variations displayed by J1819+3845 at 3.6, 6 and 13 cm wavelengths (from top to bottom) on 1 April 2002. The mean flux densities and the modulation indices at these wavelengths are given in each sub-panel. Note the good correlation between the observed variations at 3.6 and 6 cm, where the scintillations are in the weak regime **Right:** The long term trend in the mean flux density and modulation index of J1819+3845 at 6 cm. Apart from some observations by [14, 15] all observations were taken with the WSRT.

Faint polarized emission from J1819+3845 at a wavelength of 6 cm was first observed in 2000 ([19]). However, the increasing source flux density and improvement in WSRT sensitivity in 2002 suddenly made detailed studies possible. Like the total intensity, the polarized emission is variable on a timescale of tens of minutes. The variations due to scintillation are the convolution of the point-spread function of the scintillation pattern with the brightness distribution of the source structure [20]. In many 12 h syntheses in the period 2002 – 2006 we can unambiguously determine a delay between Stokes *I* and *Q* and *U* features in the lightcurve. The polarization variations typically lag those in total intensity by 1–1.5 h in the fast scintillation season (Jan-June) and correlate with the scintillation timescale, which is related to the effective projected screen velocity. A nice example
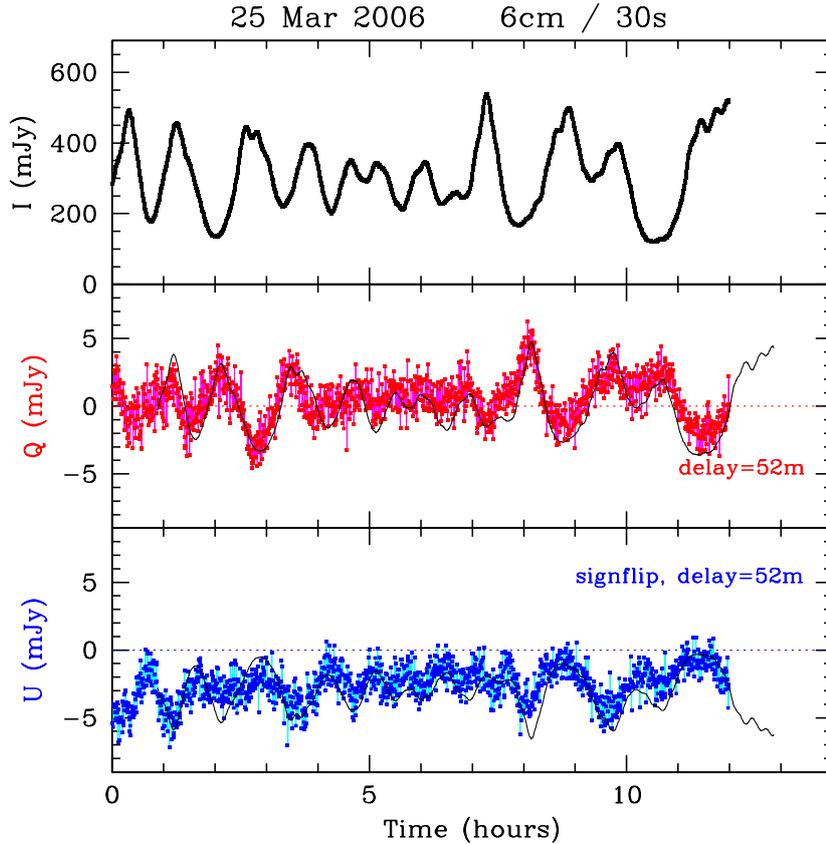
Figure 5: A demonstration of the strong correlation between polarized and unpolarized emission. The polarized emission lags the unpolarized emission indicating that the centroid of the polarized emission is angularly offset from the bulk of the unpolarized source emission. On this particular epoch, 25 Mar 2006, the delay was about 52 min and similar for both Stokes Q and U. The flux density-scaled Stokes I lightcurve is overplotted on the Stokes Q and U lightcurves. Because the Stokes U signals appear to have negative polarity on this epoch, we flipped the sign of the Stokes I signals.

is shown in Fig. 5. For a detailed discussion and more examples we refer to [1].

The VLBI data in [16] also show that the polarization structure in 2003 and 2006 shows a feature displaced about 0.6 mas to the North of the core, presumably indicating the tip of a jet. Using a model for the effective velocity in the N-S direction, orthogonal to the scintillation pattern [11], we can use the time delay to determine the linear separation of the core and polarized jet feature projected on the scintillating screen. Combining this with the angular displacement yields the distance of the screen: a mere 1–2 parsec ! This direct distance determination is in excellent agreement with the distance inferred from the very rapid (15 m full period !) variations found in 2004 and 2005 in this source [13]. During this brief period the scintillations revealed evolving fine-structure that could be due to motion at modest superluminal speeds [13]. However, for most of the period between 2000 and 2007 there is no evidence for any superluminal motion in this source.

To constrain the size of the screen we have searched in our 6 cm and 21 cm data for rapid variations in other flat spectrum sources in the vicinity of J1819+3845. We have only detected

long term variations in some flat spectrum sources 20′ to the West. We conclude that the screen that once was in front of J1819+3845 is either small or patchy. Its proximity will allow a wide variety of studies, including proper motion. For an extensive discussion of the large body of data on this source, the jet (polarization) structure and the properties of the screen, we refer to [1].
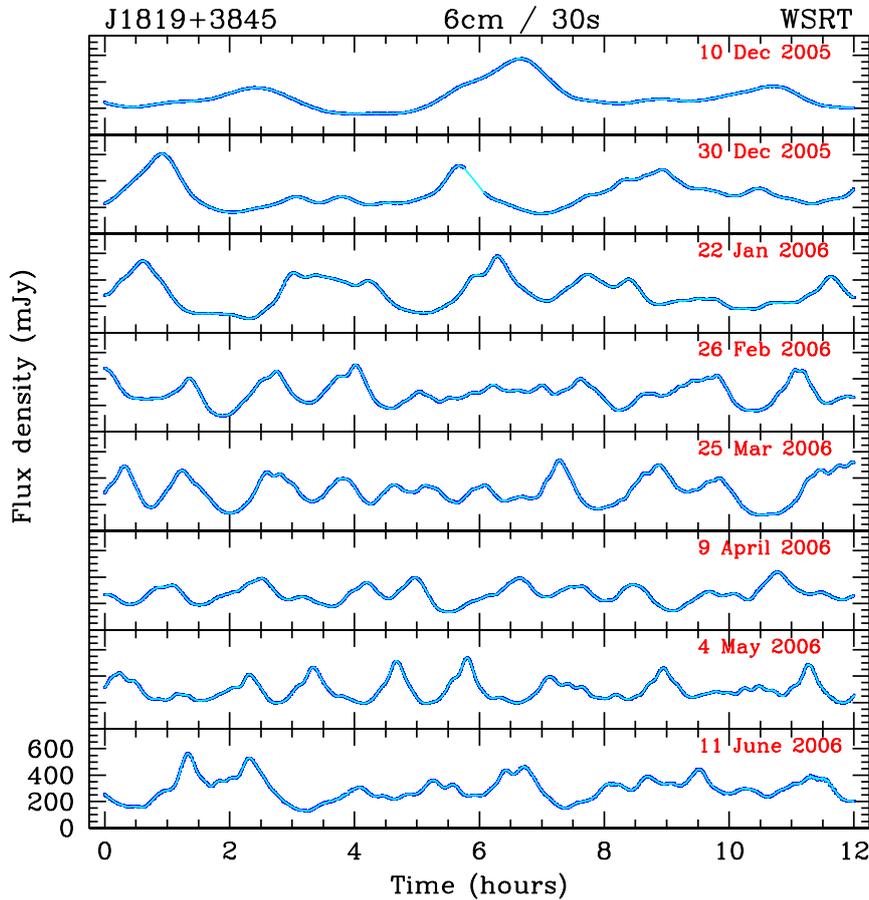
Figure 6: The 6 cm lightcurves of J1819+3845 for 8 epochs between Dec 2005 and June 2006, the last season before its dramatic scintillations vanished completely.

Acknowledgements

References

[1] A. G. de Bruyn and J.-P. Macquart, *The intra-hour variable quasar J1819+3845: 13-year evolution, jet polarization structure and interstellat scattering screen properties* , å (2012).

[2] G. R. Denn, R. L. Mutel, and A. P. Marscher, *Very Long Baseline Polarimetry of BL Lacertae*, ApJS **129** (July, 2000) 61–92.

[3] C. Reynolds, T. V. Cawthorne, and D. C. Gabuzda, *Faraday rotation in the VLBI core of BL Lacertae*, MNRAS **327** (Nov., 2001) 1071–1080.

[4] R. T. Zavala and G. B. Taylor, *A View through Faraday's Fog: Parsec-Scale Rotation Measures in Active Galactic Nuclei*, ApJ **589** (May, 2003) 126–146, [arXiv:astro-ph/0302367].

[5] G. B. Taylor and R. Zavala, *Are There Rotation Measure Gradients Across Active Galactic Nuclei Jets?*, ApJ **722** (Oct., 2010) L183–L187, [1009.3465].

[6] A. G. de Bruyn and R. T. Schilizzi, *Extended Structure around Superluminal and Other Core-Dominated Radio Sources*, in *VLBI and Compact Radio Sources* (R. Fanti, K. I. Kellermann, and G. Setti, eds.), vol. 110 of *IAU Symposium*, p. 165, 1984.

[7] M. A. Brentjens and A. G. de Bruyn, *Faraday rotation measure synthesis*, A&A **441** (Oct., 2005) 1217–1228, [arXiv:astro-ph/0507349].

[8] A. R. Taylor, J. M. Stil, and C. Sunstrum, *A Rotation Measure Image of the Sky*, ApJ **702** (Sept., 2009) 1230–1236.

[9] J. Dennett-Thorpe and A. G. de Bruyn, *The Discovery of a Microarcsecond Quasar: J1819+3845*, ApJ **529** (Feb., 2000) L65–L68, [arXiv:astro-ph/9912218].

[10] J. Dennett-Thorpe and A. G. de Bruyn, *Interstellar scintillation as the origin of the rapid radio variability of the quasar J1819+3845*, Nature **415** (Jan., 2002) 57–60, [arXiv:astro-ph/0201061].

[11] J. Dennett-Thorpe and A. G. de Bruyn, *Annual modulation in the scattering of J1819+3845: Peculiar plasma velocity and anisotropy*, A&A **404** (June, 2003) 113–132, [arXiv:astro-ph/0303201].

[12] J.-P. Macquart and A. G. de Bruyn, *Diffractive interstellar scintillation of the quasar J1819+3845 at λ21 cm*, A&A **446** (Jan., 2006) 185–200, [arXiv:astro-ph/0510495].

[13] J.-P. Macquart and A. G. de Bruyn, *Emergence and disappearance of microarcsecond structure in the scintillating quasar J1819+3845*, MNRAS **380** (Sept., 2007) L20–L24, [0705.3414].

[14] G. Cimò, *Two-Dimensional Time Delay Measurement of a fast Scintillator using VLBI arrays.*, in *The role of VLBI in the Golden Age for Radio Astronomy*, 2008.

[15] J. Y. Koay, H. E. Bignall, J.-P. Macquart, D. L. Jauncey, B. J. Rickett, and J. E. J. Lovell, *Detection of six rapidly scintillating active galactic nuclei and the diminished variability of J1819+3845*, A&A **534** (Oct., 2011) L1, [1109.1906].

[16] B. Moloney, *High-Resolution Polarisation Studies of Intra-Day Variable Sources*, Thesis, National University of Ireland, Cork (2010).

[17] G. Cimò, *A VLBI view of the extreme scintillator J1819+3845*, in *11th EVN Symposium, Bordeaux, 8-12 Oct*, 2012.

[18] R. Narayan, *The Physics of Pulsar Scintillation*, Royal Society of London Philosophical Transactions Series A **341** (Oct., 1992) 151–165.

[19] A. G. de Bruyn and J. Dennett-Thorpe, *The Microarcsecond Quasar J1819+3845: Polarization Observations and Detailed Lightcurve Analysis*, Ap&SS **278** (Oct., 2001) 139–142.

[20] B. J. Rickett, L. Kedziora-Chudczer, and D. L. Jauncey, *Interstellar Scintillation of the Polarized Flux Density in Quasar PKS 0405-385*, ApJ **581** (Dec., 2002) 103–126, [arXiv:astro-ph/0208307].