Transient Science with the e-EVN

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I briefly review transient research with the EVN, with particular emphasis on the science that was (or is being) made possible with the latest real-time e-VLBI developments.

Keywords: VLBI, e-EVN, Transients, Astrometry, Fast Radio Bursts.

1 Introduction

The European VLBI Network commenced real-time electronic VLBI operations through a limited number of dedicated 24-hour observing sessions with a subset of the telescopes in 2006; this array is sometimes referred to as the e-EVN [1]. The technical advances were accompanied by new policies that allowed for an easier access to the e-EVN for an increasing number of Target of Opportunity (ToO) observations. A well-developed calibration pipeline [2] ensures rapid access to the initial results, and the implementation of the EVN Software Correlator at JIVE (SFXC) allows for a broader range of science topics [3]. These developments guarantee flexible access to the most sensitive standalone VLBI network, making a wide range of transient science possible. The first rapid report of science observations (The Astronomer's Telegram) [4] and the first refereed journal papers [5, 6] appeared already in 2007, and these were followed by many others. It is however important to stress that it is not simply real-time correlation that makes the e-EVN a unique facility; it is the easy and open access, the high-level of support, and especially the greatly increased flexibility to follow-up transient phenomena (decreasing response time), as well as the ability to take part in multi-band campaigns outside of the regular EVN observing sessions.

2 The radio transients parameter space

In order to discuss the relevant science cases with the broader astronomical community, we organized a Lorentz Center workshop "Locating Astrophysical Transients" between 13–17 May 2013, in Leiden, the Netherlands. During this workshop the revolutionary change in the study of optical transients was set as an example. Before the advent of the major optical surveys like the Palomar Transient Factory, most of the known optical transients fitted into either the explosive (supernovae)
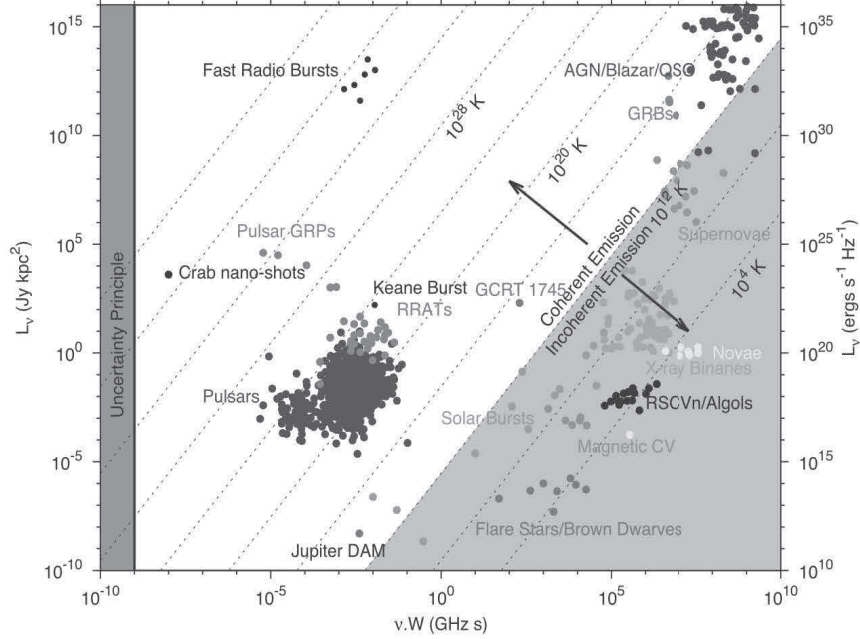
Fig. 1. Known types of radio transients shown in the phase space of specific luminosity versus product of observing frequency and transient duration ([9], Fig. 5). Note the division between the "slow" synchrotron transients, including typical EVN targets, and the "short" transients producing incoherent emission, little studied with VLBI so far. The blazar and GRB flare events are not corrected for Doppler-boosting

or eruptive (novae, luminous blue variables) categories [7]. The large field-of-view, sensitive surveys that probe a range of timescales have revealed new types of transients. One may expect to see a similar revolution in the radio regime in the era of Westerbork/APERTIF and the Square Kilometre Array (SKA), to name the two most relevant potential source of radio triggers for the e-EVN. The mid-frequency component of the first-phase SKA (SKA1-MID) will also be part of global VLBI networks as a phased-array element [8].

The radio transients parameter space is shown in Fig. 1. The events with a duration of more than a few seconds, up to several years are referred to as slow transients. These have intrinsic brightness temperatures below the inverse Compton limit ($T_{\rm b} < 10^{12}$ K), and they are mostly due to incoherent synchrotron emission. Among these sources we find several targets of VLBI interest. The events with a duration of much shorter than a few seconds are often referred to as short transients, and their emission originates in coherent processes. The Galactic counterparts of millisecond timescale pulses are neutron stars, like pulsars and Rotating RAdio Transients (RRAT). Fast Radio Bursts (FRB) show dispersion measures (DM) well above Galacitc values [10], but their positions have been too poorly constrained

to date to prove their extragalactic origin.

One of the Leiden workshop conclusions was that increasing the available observing time for real-time e-VLBI and shortening the e-EVN reaction times to triggers (on the long term, making automated triggering possible) are the ways forward to be able to follow-up a broader range of slow-transient types (Sect. 3). It was also realised that the FRB field evolves rapidly, and sub-arcsecond localisation of these events is a key to understand the nature of these sources. This requires a completely different observing approach and the need to adopt dispersed single-pulse search techniques for the e-EVN (Sect. 4).

3 Synchrotron (slow) transients

3.1 Explosive extragalactic phenomena

The obvious advantage of VLBI is source localisation at unprecedented precision. While for the astronomical interpretation arcsecond localisation would be sufficient in most cases, VLBI data have the great potential to distinguish between flaring AGN activity or other types of near-nuclear transients. The highest resolution ground-based VLBI measurements can probe non-thermal emission brightness temperatures up to about 10^{12} K, measure tiny displacements (in the 10–100 μas regime) due to a source structural change or proper motion, and can be very helpful to measure compact source total flux densities in fields with strong as-scale diffuse emission in the host galaxy. This allows the study of a broad range of astrophysical phenomena in the Local Universe ($d \leq 200$ Mpc, or $z \sim 0.05$). For 1 mas resolution the corresponding linear size is ~ 1 pc at $z = 0.05$, therefore sub-pc structures can be probed. Within this distance beamed relativistic ejecta can be resolved within a few months time, and even mildly relativistic phenomena can be studied on similar timescales up to a few tens of Mpc distance. Here we assume S/N$\gg$10, resulting in down to $\simeq 0.1$ mas reliable size measurement (cf. [11]), and ≤ 0.1 mas ejecta localisation (see e. g. [12]). Below we give a few examples of past (pre-dating e-VLBI) and recent VLBI results on various types of slow transients.

Supernovae (SNe) and gamma-ray bursts (GRB) are primary targets for VLBI because their resolved radio emission allows for probing the physical properties of their ejecta as well as their surrounding environment. Decelerating shells of ejecta have been resolved in EVN, VLBA (and global-VLBI) observations for the nearby Type 2 core-collapse events SN 1979C [13], SN 1986J [14] and SN 1993J [15, 16]. Nearby starburst galaxies provide a great opportunity to study a a number of these events in the radio simultaneously, unaffected by dust obscuration. The nuclear region of Arp220, Arp299A and M82 for example reveal a rich cluster of supernova remnants and young radio supernovae, some with peculiar properties [17, 18, 19, 20]. Asymmetric, mildly-relativistic ejecta have been suggested for some core-collapse types but these have not been confirmed [21, 22]. Type Ib/c SN 2008D has also been initially suspected to have a mildly relativistic jet, but it faded quickly before it could be resolved with the EVN [23]. It appears that — most likely — none of these latter candidates were in fact "engine driven", i. e. powered by a black
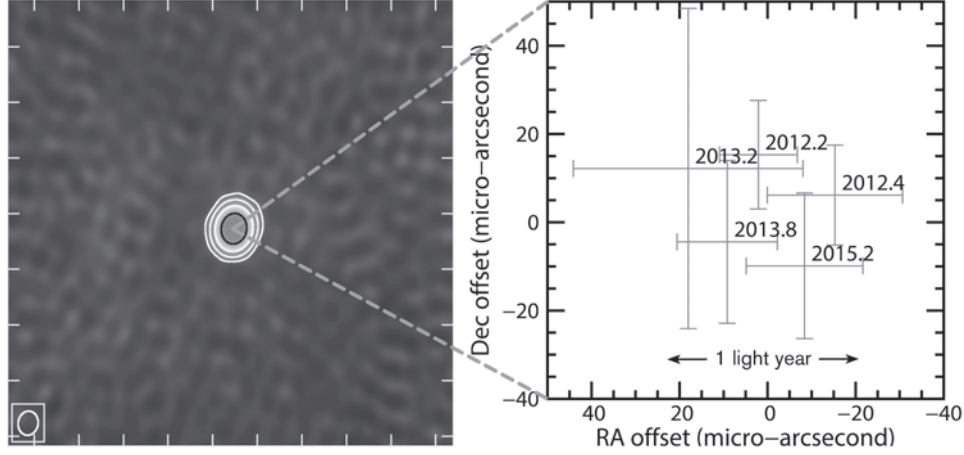
Fig. 2. EVN precision astrometry shows no proper motion in the TDE Swift J1644+5734 over three years period of time, constraining the average apparent velocity $\beta_{\mathrm{app}} < 0.27c$ ([12], from parts of Fig. 1 and Fig. 2)

hole formed in the collapse of a massive star, analogous to the highly-relativistic GRBs. Only about 1 % of all Type Ib/c supernovae belong in this category, a notable example being the broad-line Type Ib/c SN 2009bb [24]. While we have not resolved any of the GRB afterglows with VLBI besides GRB 030329 [25] yet, e-EVN data in multi-band campaigns provide useful constraints on the shock physics and the properties of the environment into which it is expanding (e. g. [26]).

Tidal Disruption Events (TDE), where tidal forces of a supermassive black hole (SMBH) disrupt a star, have received a lot of attention in the past few years. In this process dormant black holes are activated to detectable levels as they accrete part of the gas that formed the star. This allows us to study the low-mass end of the SMBH population down to $10^6 M_\odot$ and possibly below. TDE have initially been detected in X-ray surveys [27], with no trace of radio emission. But the recent detection of a prominent flare in Swift J1644+5734 from γ rays to the radio indicated that a fraction of TDE may form relativistic radio jets. What this fraction is and how relativistic these jets are is important to know in order to estimate the expected number of detectable TDE with the SKA, as SKA surveys may provide an unobscured view to these events [28]. Ultra-high precision astrometry with the EVN revealed that over three years there was no detectable proper motion in the radio ejecta of Swift J1644+5734, providing strong constraints on the intrinsic jet speed as a function of the viewing angle [12] (see Fig. 2). However, another EVN result in ASASSN-14li indicated resolved ejecta, although in that case the AGN had already been active before the TDE occured, and it is not clear at the moment whether we see a newly formed jet or not [29].

3.2 Galactic transients

Black hole X-ray binaries (XRB) — sometimes called "microquasars" — have been primary EVN targets since the earliest days of its existence, and they were among the first objects studied by real-time e-VLBI [5, 6]. But in the past it took considerable effort to reveal rapid structural changes in XRB: the most prominent steady radio-jet source SS433 was monitored for 6 days in 1985 and 1987, and this required practically all available EVN magnetic tapes [30]. The 1987 monitoring produced a spectacular show of a series of ejecta during a bright flaring event [31] — this was just pure luck. Real-time e-VLBI does not depend on recording medium at the telescopes, therefore target of opportunity or triggered (a proposal activated when certain trigger conditions are met for known transients, e. g. radio flux density and/or changes in X-ray state) observations can be scheduled in a much more flexible way today. Availability of telescope time can still be a limitation when using the e-EVN, and some of the monitoring projects are carried out jointly with the Very Long Baseline Array (VLBA; e. g. [32, 33]). These project have also demonstrated the power of e-VLBI to quickly readjust the observing schedules e. g. when suitable calibrators are found closer to the target (see e. g. Sect. 2 in [33]).

In the past fifteen years we have learned a lot about stellar black hole systems. And while it is still not clear just how relativistic black hole XRB may be, the strong connection in the accretion/ejection physics between stellar mass and supermassive black holes has been demonstrated by the discovery of the fundamental plane of black hole activity [34]. To understand accretion processes better, our attention now turns toward the lowest activity states, and also to low-mass XRB systems in which the compact object is a neutron star. For example, e-EVN observations have shown radio ejecta in Cyg X-2 following an X-ray flare (Fig. 3; [35]). But compact jets may also appear in transitional millisecond pulsars when they enter the accreting state — similar to that in low-mass XRB — evidenced by the flat spectrum and variable radio emission in PSR J1023+0038 [36].

Stellar-mass isolated black holes (IBH) may be numerous ($> 10^8$) in the Galaxy, and these may get active during short-period accretion events [37]. The Solar neighbourhood would contain $\sim$35000 IBH in a radius of 250 pc if this population exists. While the predicted X-ray and radio emissions are below the current survey limits (10^{11} erg s^{-1} and 1 mJy, respectively), these sources would show up in deep radio observations via their very high proper motion. The brightest of these (few tens of μJy) could be identified with the EVN through their observable proper motion within a day. This will require either systematic searches in large-field of view EVN data, or triggering from next generation X-ray missions.

Cataclysmic variables are binary stellar systems of an accreting white dwarf and a donor star. These produce prominent UV and X-ray flares in thermonuclear runaway events, but classical novae are strong radio emitters too. A great example is the recurrent nova RS Oph. Early EVN observations during its 1985 outburst revealed non-spherical synchrotron ejecta [38, 39], a rather controversial result at the time, because the physical model of novae assumed spherical explosions. This was
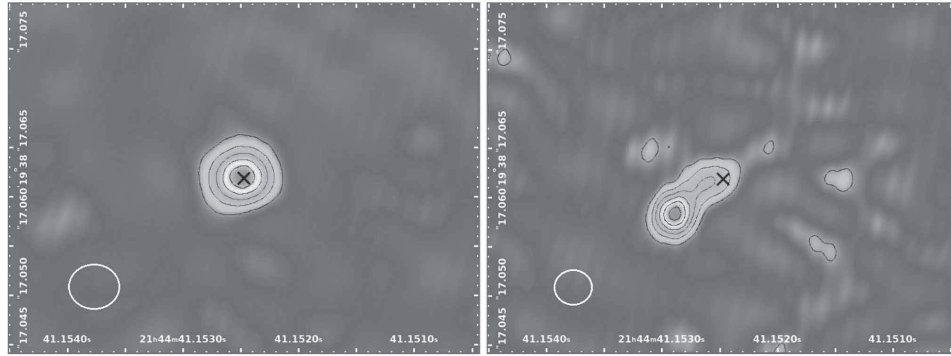
Fig. 3. 5 GHz e-EVN images separated by one day show structural changes in the low-mass XRB Cyg X-2, following an X-ray flare ([35], Fig. 1)

later confirmed with the EVN and MERLIN during the 2006 outburst of RS Oph, indicating a bi-polar, collimated outflow [40]. Further support to non-spherical ejecta in novae came with the discovery of V407 Cyg in 2010 [41] and V959 Mon in 2012 [42] that, quite unexpectedly, produced γ-ray flares as well. Monitoring observations of V959 Mon on a wide range of angular scales with the VLA, MERLIN and the e-EVN have shown a complex structure that was interpreted as the result of a slow outflow in the orbital plane and a fast polar wind; the interaction of these two regions would cause shocks (detected on milliarcsecond scales with the e-EVN) which could be the source of the γ rays as well (see Fig. 4; [42]). Nowadays it still takes a considerable effort to arrange for multiple radio facilities to monitor similar phenomena on a range of angular scales. In the near future, a merged e-EVN/e-MERLIN array and, ultimately, SKA-VLBI [8] will do a fantastic job as a single array. Besides classical novae, the great e-EVN sensitivity allows us to detect transient radio emission from dwarf novae as well; the flexible access (rapid response to triggers) is particularly relevant here, because the radio flares are short-lived (maximum 1–2 days). A precise parallax distance measurement of SS Cyg with the VLBA and the e-EVN resolved a long-standing discrepancy between accretion theory and previous observations [43].

4   Localizing Fast Radio Bursts

The first FRB was found in Parkes data and was reported in 2007 [10]. The field progressed slowly in the beginning, but following the announcement of 4 Parkes FRB in 2013 [44] many other instruments initiated millisecond pulse searches*. Till now the only evidence for the extragalactic origin of these bursts is their large dispersion measure, well in excess of the NE2001 model [45] predicted Galactic value in their line of sight. But if truly distant, they could serve as a cosmological probe since the distribution of their DMs would tell us — among others — the baryonic

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*Dan Thornton presented these results at the 2013 Lorentz Center workshop mentioned above, and the potential of possible EVN localization were discussed there.
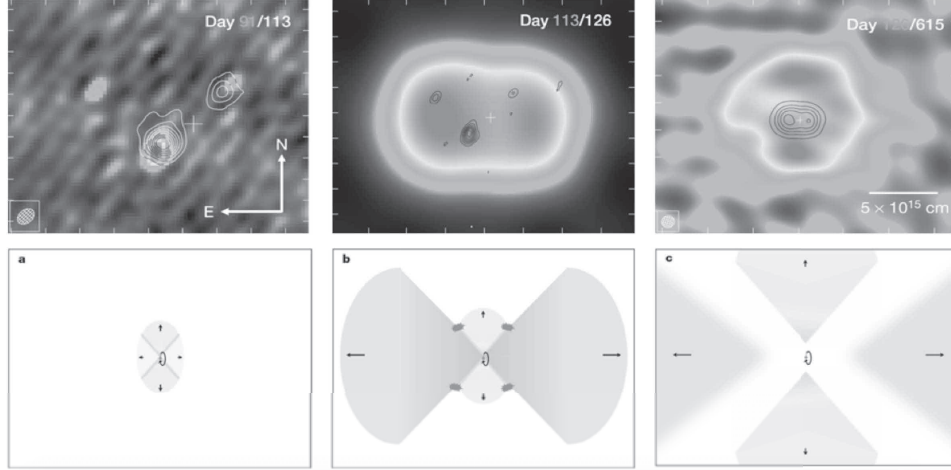
Fig. 4. Various phases of V959 Mon ejecta evolution. Above: comparison of e-EVN (day 91/113) and VLA (day 126/615) images. Below: schematic illustration of the dense, slow outflow in the orbital plane, and the fast polar outflow; their interaction causes the shocks seen on VLBI scales ([42], re-ordered Fig. 2 and Fig. 3)

content of the Universe. The only way to prove this is direct localization using interferometric methods, and measuring the redshift for the optical counterpart. Recently Keane et al. reported near-real time ATCA follow-up of FRB 150418, that showed a transient radio source in a galaxy with redshift $z = 0.49$ [46]. It has been proposed by others that the claimed counterpart is a scintillating AGN; indeed e-EVN data show support for the presence of an AGN in the galaxy (but the strong variability was not observed) [47].

The most direct way to identify FRB counterparts is to detect these few-milli-second events in interferometric observations, and image them. A commensal search for FRBs started at the VLBA (V-FASTR Experiment), but after four years only upper limits on the FRB rate could be derived [48]. The EVN has more sensi-tive dishes, but the field of view of the larger antennas are proportionally smaller as well, thus the advantages of a similar commensal search are not straightfor-ward. There are however preparations within the (unfunded) LOCATe project at JIVE to establish an FRB detection pipeline. The idea is to search for single, dis-persed pulses in autocorrelation data of the telescopes using standard pulsar soft-ware tools. The data have to be RFI filtered first — the old MkIV format EVN data caused a lot of problems initially because the regular data headers in the data streams were misinterpreted as RFI by the various pulsar tools. The automatic gain control (AGC) system and the 80 Hz calibrations signal (first started at Effelsberg) are also not an advantage for single-pulse search. The most disturbing external broad-band RFI is mitigated by a technique called zero-DM subtraction [49], also used for pulsar searches at Parkes. A schematic representation of the single-pulse search process is shown in Fig. 5, along with a bright double-pulse found in our
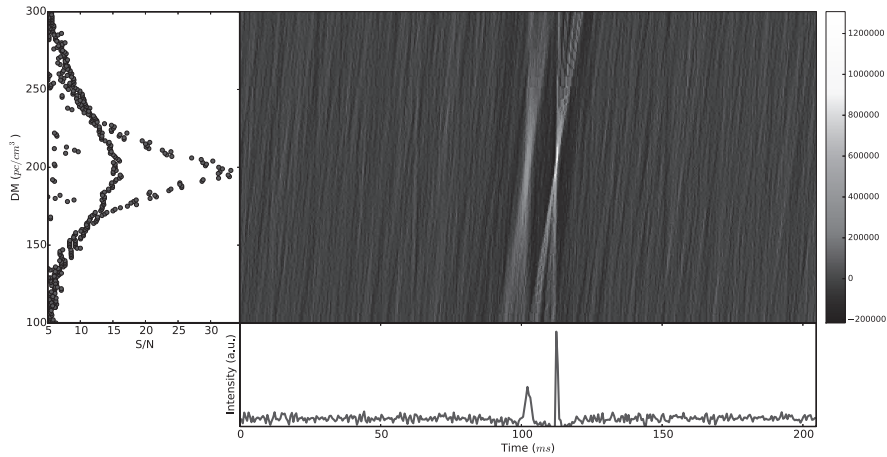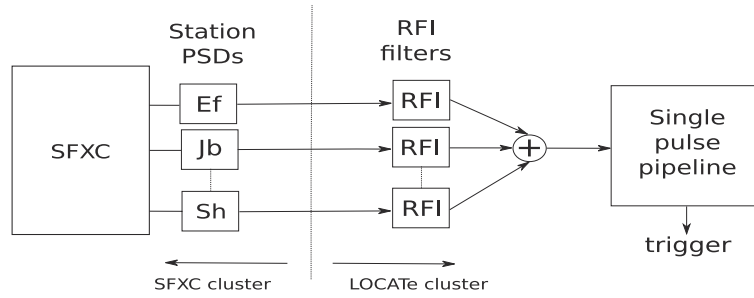
Fig. 5. Above: simplified flowchart of searching for millisecond-duration pulses in e-EVN data in the LOCATe project. Below: bright, double pulse detected in RRAT J1819−1458, allowing image-plane localization using the VLBI data

test source RRAT J1819-1458. When a pulse is found, that tiny bit of data is dedispersed and recorrelated with a very fine time and frequency resolution. The following image-plane localization is a very simple process: one should take the calibration of the original (phase-referencing) dataset, apply the calibration tables to the recorrelated data, and form a (series of) image(s). Since the uv-coverage is very poor, and the visibility errors in ms-pulse uv-data are poorly understood, one must be careful interpreting the images (Huang et al. in prep.).

To apply this technique to FRBs has just become possible with the Arecibo discovery of repeated bursts from FRB 121102 [50]. Following the initial VLA localization [51], the EVN provided a position to the burst source at the 10-mas level [52], showing that it is co-located with a weak, persistent radio source in a galaxy with a redshift of 0.1927 [53]. These observations provided the first direct evidence for the cosmological origin of a fast radio burst.

Acknowledgements

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