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Arp 299-A: More than "just" a prolific supernova factory

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We present partial results from our monitoring of the nuclear region of the starburst galaxy IC 694 (=Arp 299-A) at radio wavelengths, aimed at discovering recently exploded core-collapse supernovae, as well as to determine their rate of explosion, which carries crucial information on star formation rates and starburst scenarios at work.

Two epochs of eEVN observations at 5.0 GHz, taken in 2008, revealed the presence of a rich cluster of compact radio emitting sources in the central 150 pc of the nuclear starburst in Arp 299A. The large brightness temperatures observed for the compact sources indicate a non-thermal origin for the observed radio emission, implying that most, if not all, of those sources were young radio supernovae and supernova remnants. More recently, contemporaneous EVN observations at 1.7 and 5.0 GHz taken in 2009 have allowed us to shed light on the compact radio emission of the parsec-scale structure in the nucleus of Arp 299-A. Namely, our EVN observations have shown that one of the compact VLBI sources, A1, previously detected at 5.0 GHz, has a flat spectrum between 1.7 and 5.0 GHz and is the brightest source at both frequencies. The morphology, radio luminosity, spectral index and ratio of radio-to-X-ray emission of the A1-A5 region allowed us to identify A1-A5 with long-sought AGN in Arp 299-A. This finding may suggest that both starburst and AGN are frequently associated phenomena in mergers. Finally, we also note that component A0, identified as a young RSN, exploded at the mere distance of two parsecs from the putative AGN in Arp 299-A, which makes this supernova one of the closest to a central supermassive black hole ever detected.

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1. Introduction

A large fraction of the massive star-formation at both low- and high-z has taken place in (U)LIRGs. Thus, their implied high star-formation rates (SFRs) are expected to result in CCSN rates a couple of orders of magnitude higher than in normal galaxies. Therefore, a powerful tracer for starburst activity in (U)LIRGs is the detection of CCSNe (see, e.g., [1] and references therein), since the SFR is directly related to the CCSN rate. However, most SNe occurring in (U)LIRGs are optically obscured by large amounts of dust in their nuclear starburst environments, and have therefore remained undiscovered by (optical) SN searches. Fortunately, it is possible to discover these CCSNe through high-resolution radio observations, as radio emission is free from extinction effects. Furthermore, CCSNe are expected, as opposed to thermonuclear SNe, to become strong radio emitters when the SN ejecta interact with the circumstellar medium (CSM) that was ejected by the progenitor star before its explosion as a supernova. Therefore, if (U)LIRGs are starburst-dominated, bright radio SNe are expected to occur and, given its compactness and characteristic radio behaviour, can be pinpointed with high-angular resolution, high-sensitivity radio observations (e.g., SN 2000ft in NGC 7469 [2, 3, 4]; SN 2004ip in IRAS 18293-3413, [5]; SN 2008cs in IRAS 17138-1017, [6], [7]; supernovae in Arp 299 [8], Arp 220 [9, 10, 11], Mrk 273 [12]). However, since (U)LIRGs are likely to have an AGN contribution, it is mandatory the use of high-sensitivity, high-resolution radio observations to disentangle the nuclear and stellar (mainly from young SNe) contributions to the radio emission, thus probing the mechanisms responsible for the heating of the dust in their (circum-)nuclear regions.

2. e-EVN and full-EVN imaging of Arp 299-A

Arp 299 (the merging system formed by IC 694 and NGC 3690) is the "original" starburst galaxy [13] and an obvious merger system that has been studied extensively at many wavelengths. An active starburst in Arp 299 is indicated by the high frequency of recent optically discovered supernovae in the outer regions of the galaxy. Since the far infrared luminosity of Arp 299 is $L_{IR} \approx 6.5 \times 10^{11} L_{\odot}$, the implied CCSN rate is of $\approx$1.7 SN/yr. Given that 50% of its total infrared emission comes from source A (see top panel of Fig. 1), it is expected that $\sim$0.9 SN/yr will explode in region A. Therefore, this region is the one that shows most promises for finding new supernovae. Indeed, Neff et al. (2004) found a new component in this region, by comparing VLBA observations carried out in April 2002 and February 2003.

We used the electronic European VLBI Network (e-EVN) [14] to image Arp 299-A at a frequency of 5 GHz over 2 epochs, to directly detect recently exploded core-collapse supernovae (CCSNe) by means of the variability of their compact radio emission. The attained off-source root-mean-square (rms) noise level was 39 μJy/beam and 24 μJy/beam for the 8 April 2008 and 5 December 2008 observations, respectively, and enabled us to detect more than 20 compact components above 5 rms (see Fig. 1 and [15]). Since the EVN radio image on 5 December 2008 is much deeper than the one obtained on 8 April 2008, it is not surprising that we detected a larger number of VLBI sources in our second epoch (25) than in our first one (15). This allowed us to go back to our first-epoch image and extract the flux density for the new components (A15 through to A25 in Fig. 1), which show $\geq$ 5 rms detections only in the December 2008 image. This procedure allowed us to recover four components above 3σ (A15, A18, A22, and A25), based on a positional coincidence with the peak of brightness of our second epoch of greater than ~ 0.5 milliarcsec, i.e., much smaller than the synthesized interferometric beam).

These e-EVN observations showed the existences of a very compact, rich nuclear starburst in Arp 299-A. The angular size encompassed by the radio emitting sources in Arp 299-A is smaller than 0.7"$\times$0.4", corresponding to a projected linear size of (150$\times$85) pc.

In 2009, we used the European VLBI Network (EVN) to image the central regions of Arp 299-A at 1.7 GHz on 7-8 June, and at 5.0 GHz on 12-13 June. We used a sustained data recording rate of 1024 Mbit s^{-1} in two-bit sampling. Each frequency band was split into eight intermediate frequencies (IFs) of 16 MHz bandwidths each, for a total synthesized bandwidth of 128 MHz. We followed the same calibration and imaging scheme used for our e-EVN observations, as described in [15]. The final images are shown in Figure 2, and were obtained by applying natural weighting to the data, which resulte FWHM, synthesized interferometric beams of (11.9 mas $\times$ 4.4 mas at PA=-76°) and (5.0 mas $\times$ 4.1 mas at PA=7°) at 1.7 and 5.0 GHz, respectively. The attained 1σ off-source r.m.s noise was of $\sim 25\,\mu$Jy at 1.7 GHz and $\sim 22\,\mu$Jy at 5.0 GHz.

3. Summary and discussion

We have presented results obtained from our e-EVN and full-EVN monitoring of the nuclear region of Arp 299-A at 1.7 and 5.0 GHz.

Two epochs of eEVN observations at 5.0 GHz, taken in 2008, revealed the presence of a rich cluster of compact radio emitting sources in the central 150 pc of the nuclear starburst in Arp 299A, which were mostly identified with young radio supernovae (RSNe) and supernova remnants (SNRs). Those objects identified as RSNe show radio luminosities that are typical of Type II L and/or Type IIb supernovae, and several of them show strong indications of having exploded in the last few years. We also note that many of them seem to follow a rather slow evolution, as opposed to the usually rapid evolution of RSNe in normal galaxies, and argue that this must be due to the CSM in the nuclear regions of Arp 299-A being much denser than the CSM encountered in normal galaxies.

Our contemporaneous, full-EVN observations at 1.7 and 5.0 GHz taken in June 2009, have allowed us to shed light on the compact radio emission of the parsec-scale structure in the nucleus of Arp 299-A. Namely, our EVN observations have shown that one of the compact VLBI sources, A1, previously detected at 5.0 GHz, has a flat spectrum between 1.7 and 5.0 GHz and is the brightest source at both frequencies. The morphology, radio luminosity, spectral index and ratio of radio-to-X-ray emission of the A1-A5 region allowed us to identify A1-A5 with long-sought AGN in Arp 299-A. This finding may suggest that both starburst and AGN are frequently associated phenomena in mergers. Finally, we also note that component A0, identified as a young RSN, exploded at the mere distance of two parsecs from the putative AGN in Arp 299-A, which makes this supernova one of the closest to a central supermassive black hole ever detected.

Our ongoing monitoring of Arp 299-A might allow us to directly, and independently of models, determine its CCSN rate. This would be of crucial relevance for LIRG studies, since the CCSN rate carries crucial information on the massive star formation rate and starburst scenarios at work in LIRGs.

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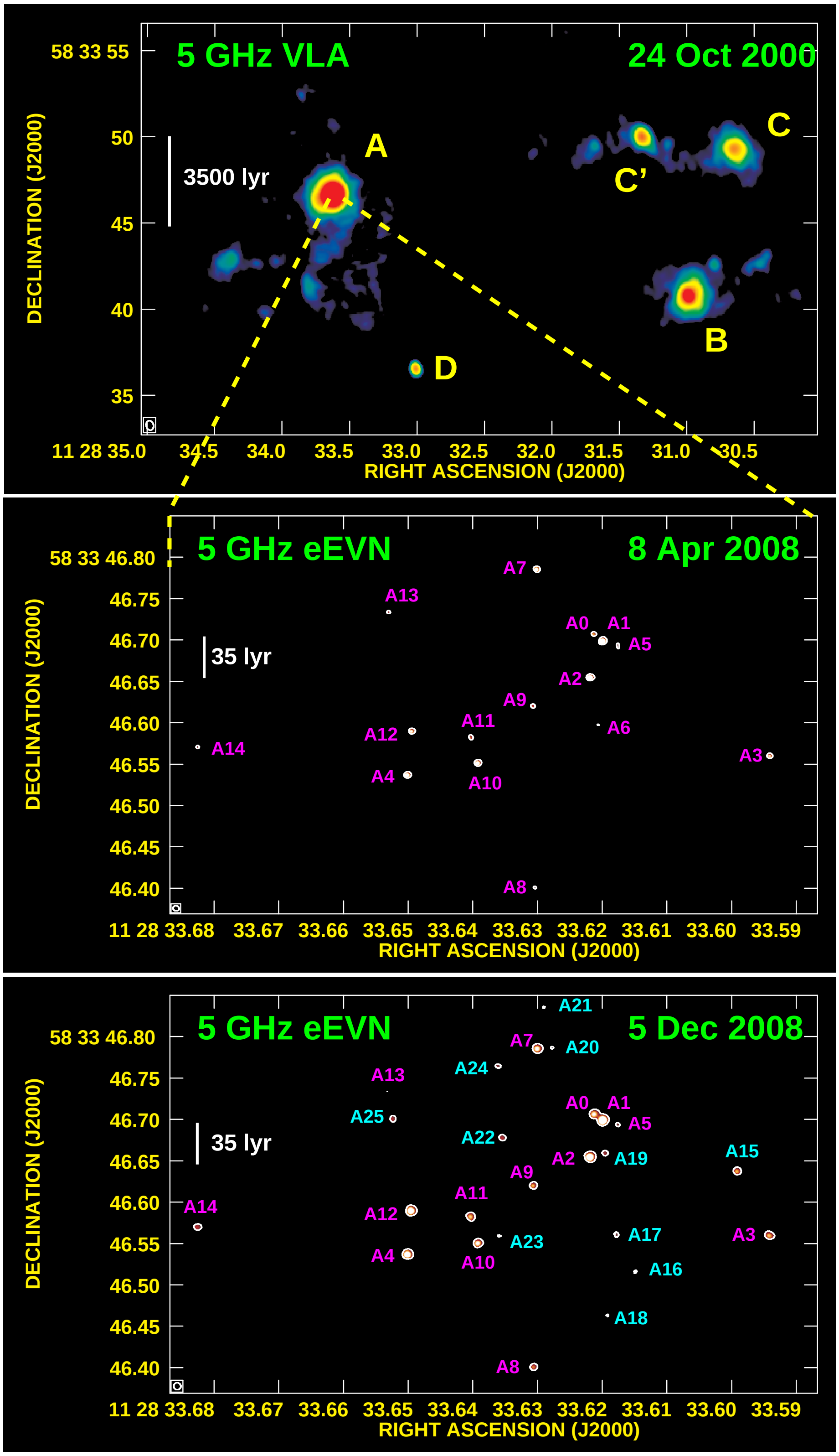

Figure 1: *Top panel:* 5 GHz VLA archival observations of Arp 299 on 24 October 2000, displaying the five brightest knots of radio emission in this merging galaxy. *Middle and bottom panels:* 5 GHz e-EVN observations of the central 500 light years of Arp 299-A on 8 April 2008 and 5 December 2008. The off-source root-mean-square (r.m.s.) noise level is 39 μJy/beam and 25 μJy/beam for the middle and bottom panels, respectively, and show the existence of 15 and 26 compact components with a signal-to-noise ratio (s.n.r.) equal or larger than five on 8 April 2008 and 5 December 2008, respectively. The size of the FWHM synthesized interferometric beam was of (0.6 arcsec $\times$ 0.4 arcsec) for the VLA observations, and of (7.3 milliarcsec $\times$ 6.3 milliarcsec) and (8.6 milliarcsec $\times$ 8.4 milliarcsec) for the e-EVN observations on 8 April 2008 and 5 December 2008, respectively.

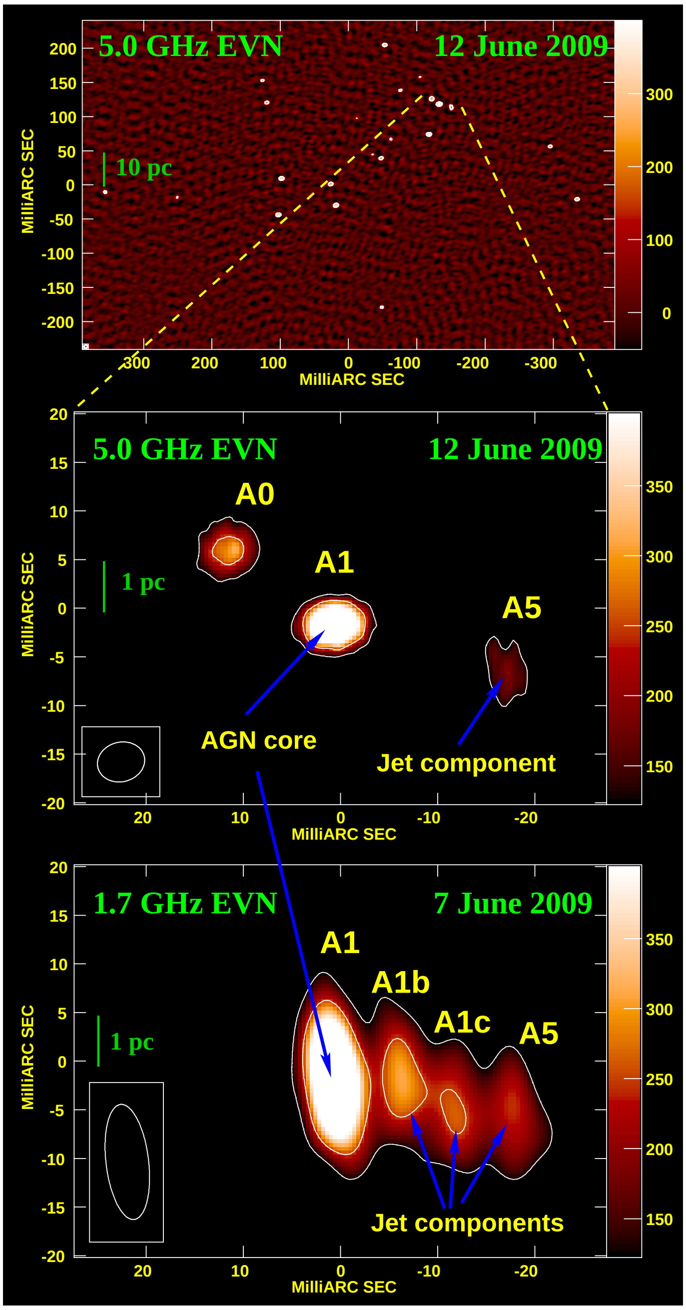

Figure 2: *Top:* 5.0 GHz full EVN image of the central 150 parsec region of the luminous infrared galaxy Arp 299-A (=IC 694), displaying a large number of bright, compact, nonthermal emitting sources, mostly identified with young RSNe and SNRs. The image center is at RA 11:28:33.63686 and DEC 58:33:46.5806. *Middle and bottom:* Blow-ups of the inner 8 parsec of the nuclear region of Arp 299-A, as imaged with the full EVN at 1.7 and 5.0 GHz. The image center is at RA 11:28:33.61984 and DEC 58:33:46.7006 in both panels. The morphology, spectral index and luminosity of the A1-A5 region are very suggestive of a core-jet structure. The color scale goes from -50 μJy/b up to 400 μJy/b in the top panel and from 125 μJy/b to 400 μJy/b in the middle and bottom panels. Contours are drawn at 5 and 10 times the off-source r.m.s. noise.

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