LETTER TO THE EDITOR

An extremely prolific supernova factory in the buried nucleus of the starburst galaxy IC 694*

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ABSTRACT

Context. The central kiloparsec of many local luminous infrared galaxies are known to host intense bursts of massive star formation, leading to numerous explosions of core-collapse supernovae (CCSNe). However, the dust-enshrouded regions where those supernovae explode hamper their detection at optical and near-infrared wavelengths.

Aims. We investigate the nuclear region of the starburst galaxy IC 694 (=Arp 299-A) at radio wavelengths, aimed at discovering recently exploded CCSNe, as well as determining their rate of explosion, which carries crucial information about star formation rates, the initial mass function, and the starburst processes in action.

Methods. We use the electronic European VLBI Network to image with milliarcsecond resolution the 5.0 GHz compact radio emission of the innermost nuclear region of IC 694.

Results. Our observations detect a rich cluster of 26 compact radio emitting sources in the central 150 pc of the nuclear starburst in IC 694. The high brightness temperatures observed for the compact sources are indicative of a non-thermal origin for the observed radio emission, implying that most, if not all, of those sources are young radio supernovae (RSNe) and supernova remnants (SNRs). We find evidence of at least three relatively young, slowly evolving, long-lasting RSNe (A0, A12, and A15) that appear to have unusual properties, suggesting that the conditions in the local circumstellar medium (CSM) play a significant role in determining the radio behaviour of expanding SNe. Their radio luminosities are typical of normal RSNe, which result from the explosion of type IIP/b and type IIL SNe. All of these results provide support for a recent (less than 10–15 Myr) instantaneous starburst in the innermost regions of IC 694.

Key words. galaxies: starburst – stars: supernovae: general – radiation mechanisms: non-thermal – radio continuum: stars – galaxies: individual: IC 694 – galaxies: luminosity function, mass function

1. Introduction

The observed rate at which massive stars \(M \geq 8 M_\odot\) die as CCSNe, \(v_{\text{CCSN}}\), can be used as a direct measurement of the current star formation rate (SFR) in galaxies, and provides unique information about the initial mass function (IMF) of massive stars. While the rate at which stars die in normal galaxies is rather low (e.g., one SN is expected to explode in the Milky Way every \(\sim 50\) yr), the CCSN rate in luminous and ultraluminous infra-red galaxies (LIRGs, \(L_\text{IR} \geq L[8-1000 \mu\text{m}] \geq 10^{11} L_\odot\); and ULIRGs, \(L_\text{IR} \geq 10^{12} L_\odot\); Sanders & Mirabel 1996) is expected to be at least one or two orders of magnitude higher than in normal galaxies (Condon 1992), and hence detections of SNe in (U)LIRGs offer a promising way of determining the current star formation rate in nearby galaxies.

However, the direct detection of CCSNe in the extreme densities of the central few hundred pc of (U)LIRGs is extremely difficult, since emission in the visual band suffers very significant extinction in those regions, which contain large amounts of dust, and can at best yield only an upper limit to the true value of \(v_{\text{CCSN}}\). Fortunately, it is possible to directly probe the star-forming activity in the innermost regions of (U)LIRGs by means of high angular resolution \((\leq 0.05\) arcsec\), high-sensitivity \((\leq 0.05\) mJy\)) radio searches of CCSNe, as radio emission is unaffected by dust extinction, and the angular resolution yielded by current Very Long Baseline Interferometry (VLBI) arrays, of the order of a few milliarcsec at cm-wavelengths, is able to detect individual radio supernovae at large distances in the local Universe.

Starburst activity in the circumnuclear regions of (U)LIRGs implies both the presence of a high number of massive stars and a dense surrounding medium, so bright radio SNe are expected to occur (Chevalier 1982; Chugai 1997), and high-resolution radio observations have shown that highly extinguished CCSNe do exist in the circumnuclear \((r \leq 1\) kpc\) region of local (U)LIRGs (Smith et al. 1998; Lonsdale et al. 2006; Colina et al. 2001; Neff et al. 2004; Pérez-Torres et al. 2007; Kankare et al. 2008). Therefore, VLBI observations can place strong constraints on the properties of star formation in the dust-enshrouded environments encountered in (U)LIRGs.

Arp 299 consists of two interacting galaxies (IC 694 and NGC 3690), which are in an early merger stage (Keel & Wu 1995). At a luminosity distance of 44.8 Mpc (Fixsen et al. 1996) for \(H_0 = 73\) km s\(^{-1}\) Mpc\(^{-1}\), Arp 299 has an infrared luminosity \(L_\text{IR} \approx 6.7 \times 10^{11} L_\odot\) (Sanders et al. 2003), which almost qualifies it as a ULIRG. The innermost \(~150\) pc nuclear

* Tables 1, 2 and Appendix are only available in electronic form at http://www.aanda.org
region of Arp 299-A (see Fig. 1) is heavily dust-enshrouded, thus making the detections of SNe very challenging even at near-infrared wavelengths. Yet, Arp 299 hosts recent and intense star-forming activity, as indicated by the relatively high frequency of supernovae discovered at optical and near-infrared wavelengths in its outer, much less extinguished regions (Forti et al. 1993; van Buren et al. 1994; Li et al. 1998; Yamaoka et al. 1998; Qiu et al. 1999; Mattila et al. 2005).

The brightest component at infrared and radio wavelengths is IC 694 (A in the top panel of Fig. 1; hereafter Arp 299-A), which accounts for ~50% of the total infrared luminosity of the system (Alonso-Herrero et al. 2000; Charmandaris et al. 2002), and ~70% of its 5 GHz radio emission (Neff et al. 2004). Numerous H II regions populate the system near star-forming regions, which implies that star formation has been occurring at a high rate for past ~10 Myr (Alonso-Herrero et al. 2000). Given that IC 694 accounts for most of the infrared emission in Arp 299, it is the region that is most likely to contain new SNe (Condon 1992). Since optical and near-infrared observations are likely to miss a significant fraction of CCSNe in the innermost regions of Arp 299-A due to high values of extinction ($A_V \sim 34 - 40$, Gallais et al. 2004; Alonso-Herrero et al. 2009) and the lack of the necessary angular resolution, radio observations of Arp 299-A at high angular resolution, high sensitivity are the only way of detecting new CCSNe and measuring directly and independently of any model its CCSN and star formation rates. Very Long Baseline Array (VLBA) observations carried out during 2002 and 2003 resulted in the detection of five compact sources (Neff et al. 2004), one of which (A0) was identified as a young SN.

### 2. eEVN observations and results

We used the electronic European VLBI Network (e-EVN) (Szomoru 2006) to image Arp 299-A at a frequency of 5 GHz over 2 epochs, to directly detect recently exploded core-collapse supernovae by means of the variability of their compact radio emission (see Appendix A for a detailed description of our observing strategy, calibration and imaging procedures, and source detection and techniques for flux density extraction). 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 enables 26 compact components to be detected above 5 rms (see Fig. 1). 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 ≥5 rms detections only in the December 2008 image. This procedure allowed us to recover four components above 3σ ($A_{15}, A_{18}, A_{22},$ and $A_{25}$), 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.

Our results demonstrate that a very compact rich nuclear starburst in Arp 299-A exists and, in general, are in excellent agreement with independent results reported by Ulvestad (2009). 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 × 85) pc. To facilitate comparisons, we define here a fiducial supernova radio luminosity equal to three times the image rms in the 8 April 2008 epoch, which corresponds to $2.9 \times 10^{41}$ erg s$^{-1}$ Hz$^{-1}$. In this way, the radio luminosities for the VLBI components range between 1.1 ($A_{25}$) and 7.3 ($A_{1}$) and between 1.0 ($A_{13}$) and 7.7 ($A_{1}$) times the fiducial value, for the VLBI observations on 8 April 2008 and 5 December 2008, respectively (see Table 1 for details).

### 3. Discussion

The radio emission from the compact sources detected from our VLBI observations can be explained in principle within two different physical scenarios: (i) thermal radio emission from super star clusters (SSCs) hosting large numbers of young,
massive stars that ionize surrounding H II regions; (ii) non-
thermal radio emission from supernova remnants (SNRs) and/or
young radio supernovae (RSNe), i.e., recently exploded core-
collapse supernovae where the interaction of their ejecta with
their surrounding circumstellar or interstellar medium (CSM or
ISM, respectively) would give rise to significant amounts of syn-
chrotron radio emission.

The existence of SSCs in Arp 299-A has been demonstrated
by their apparent detection using 2.2-μm adaptive optics imaging
(Lai et al. 1999). Further evidence comes from Hubble Space
Telescope (HST) FOC and NICMOS images, which reveal a
population of young stellar clusters in the central regions of
Arp 299 (Alonso-Herrero et al. 2000). The total 5.0 GHz radio
luminosity in compact sources is $1.7 \times 10^{26}$ erg s$^{-1}$ Hz$^{-1}$ and
$2.0 \times 10^{28}$ erg s$^{-1}$ Hz$^{-1}$ on 8 April 2008 and 5 December 2008,
respectively. However, the high flux densities and small sizes
of most of the compact sources in Arp 299-A ($\leq$ 0.2 milliarcsec;
see Table 2), are indicative of brightness temperatures, $T_B$,
that greatly exceed the thermal temperatures expected from SSCs
($\leq 2 \times 10^4$ K), thus ruling out a thermal origin of the compact
radio emission traced by our eEVN observations.

Therefore, the observed radio emission must be generated
by young radio supernovae, SNRs, or both. In Table 1, we show
the flux densities and luminosities of all the components iden-
tified in our observations, and classify the objects according to
their variability. The majority of sources do not show any evi-
dence of significant variability, which is consistent with their
identification as SNR. Only three sources (A6, A12, and A15)
show appreciable flux density variations between our two con-
secutive VLBI observations (see Table 1 for details), which is
very difficult to reconcile with their radio emission being pro-
duced by SNRs. A6, A12, and A15 are also detected in previous
VLBI observations between 2003 and 2005 by Ulvestad (2009),
where he reports that he finds no evidence of significant vari-
ability at the $\sim$20% level. However, the individual flux densities
at the various epochs of observation are not listed in his paper,
which makes a detailed comparison with our data problematical.
During 18 months, a recent RSN may have indeed gone from
very low to very high flux density values, and even have faded
away completely. Nevertheless, from his non-detection of A15 at
2.3 GHz, and our clear detection with an increasing flux density
over two epochs at 5.0 GHz, we suggest that A15 is a relatively
recent, slowly evolving RSN. This behaviour is very similar to
that displayed by A0 (see below). Similarly, source A12 has a
flux that is increasing with time at 5.0 GHz; and since it was
also previously detected in 2003 and 2005, it too is likely to be
a relatively recent and slowly evolving RSN. The nature of A6
is less clear. Ulvestad (2009) detected A6 only at 2.3 GHz. This
detection, together with the sudden drop in its 5.0 GHz flux den-
sity between April and December 2008 may be interpreted as the
result of a CCSN leaving its young radio supernova phase (when
its radio emission is powered by interaction with the CSM)
and entering a supernova remnant phase (when it is powered by
interaction with the ISM). We cannot exclude, however, the possi-
ability that A6 is an X-ray binary or a microquasar. A6 is quite
close to two X-ray sources reported by Zezas et al. (2003) (sources 14
and 16 in their Table 1). The combined absorption corrected X-ray
luminosity of those sources is $\sim 1.9 \times 10^{40}$ erg s$^{-1}$. From
the 5.0 GHz radio luminosity of A6 in Table 1, and assuming
a spectral index of $a = -0.5$ (typical of microquasars), the ap-
proximate total radio luminosity is $\sim 4.8 \times 10^{36}$ erg s$^{-1}$, result-
ing in a ratio of radio to X ray luminosity of $\sim 2.5 \times 10^{-4}$, which
is quite high, but still compatible with A6 being a microquasar.
Approved new EVN high-sensitivity observations will allow us
to confirm the nature of A6 in the near future.

The maximum 5.0 GHz luminosities inferred for A12 and
A15 are $\sim 1.6 \times 10^{27}$ erg s$^{-1}$ Hz$^{-1}$ and $7.6 \times 10^{26}$ erg s$^{-1}$ Hz$^{-1}$,
respectively. Those radio luminosities are typical of radio emit-
ting type IIP, or type Ib SNe (Chevalier 2006). If confirmed, it
would be the first time that these relatively faint radio SNe have
been detected in the nuclear starburst of a local (U)LIRG. For
comparison, Arp 220 appears to contain essentially very bright
radio supernovae, which are identified with type Ibn SNe (Parra
et al. 2007). We note here that this is not simply a sensitivity
issue, since some of the VLBI observations of Arp 220 had an
rms as low as 9 μJy/b (Parra et al. 2007), yet most of the ob-
jects detected were identified, based on their high radio lumi-
nosities, as type Ibn SNe. We cannot exclude, however, that A12
and A15 have not yet reached their peak luminosity. In this case,
their (peak) radio luminosity should be a few times higher, and
given their slow evolution, these SNe could be type IIL, or even
type Ibn.

In a previous paper, Neff et al. (2004) reported the detec-
tion of five VLBI sources (A0 to A4), within the central $\sim$80 pc
of Arp 299-A. We detect all of these components at 5.0 GHz.
Components A1 to A4 do not exhibit significant variability in
the eight months covered by our 5.0 GHz eEVN observations,
which is consistent with them being young supernova remnants,
as also suggested by Ulvestad (2009).

First detected at 8.4 GHz, A0 was identified with a radio
supernova by Neff et al. (2004). We have now detected it at
5.0 GHz, more than five years after its discovery at 8.4 GHz. This
implies that A0 is a long-lasting, slowly evolving, non-standard
radio supernova, since most other examples evolve more rapidly
(Weiler et al. 2002). Although rather uncommon, there are simi-
cular cases reported in the literature, in both normal galaxies, e.g.,
SN 1979C in M100 Montes et al. (2000), and (U)LIRGs, like
some of the RSNe in Arp 220 (Parra et al. 2007). In addition,
its non-detection at 2.3 GHz until 2005 (Ulvestad 2009) is in-
dicative of a foreground absorber (e.g., a nearby H II region),
as in the case of SN 2000ft in the LIRG NGC 7469 (Alberdi
et al. 2006; Pérez-Torres et al. 2009). Finally, we note that A5
may also have similar properties, although its variability signifi-
cance is lower. In short, the behaviour displayed by A0 (and A5)
whilst unusual, is not unknown for an RSN, and provides im-
portant information about how the interaction between the SN
and CSM is proceeding, and thus probes the mass-loss history of
the progenitor star. We therefore suggest that it is the local
CSM conditions that are primarily responsible for determining

![Fig. 2.](image-url)
the power of the radio supernovae exploding in the nuclear starburst of Arp 299-A.

e-EVN observations show that Arp 299-A hosts an extremely prolific supernova factory, with radio luminosities typical of type Ib, IIp, and IIl, and provides strong support to the scenario proposed by Alonso-Herrero et al. (2000), which proposes the existence of a recent (less than 10–15 Myr old), intense, instantaneous starburst. We find evidence of at least three slowly evolving, long-lasting, non-standard RSNe (A0, A12, and A15), which is very indicative of local CSM conditions playing a main role in determining the radio behaviour of the exploding SNe. Our current monitoring of Arp 299-A with the eEVN at 5.0 GHz, which is scheduled to continue until the end of 2010, should allow us to detect any new radio supernova, and therefore test whether the IMF in Arp 299-A is top-heavy, in contrast with to the conventional Salpeter (Salpeter 1955), or Kroupa (Kroupa 2001) IMFs, where the production of massive stars (\( M \gtrsim 8 M_\odot \)) that eventually produce CCSNe is low compared to the production of less massive stars. There seems to be evidence that this might also be the case of M 82 (Doane & Mathews 1993) and Arp 220 (Parra et al. 2007), and theoretically it is expected that in the warm, dense, ISM conditions within a (U)LIRG, the IMF should indeed be top-heavy because of a higher Jeans mass (Klessen et al. 2007).

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**Table 1.** Compact radio-emitting sources in the central region of Arp 299-A.

| Source name | Source type | $\Delta \alpha^{a}$ (J2000.0) | $\Delta \delta$ (J2000.0) | $S_\nu$ ($\mu$Jy)$^{b}$ | $L_\nu/10^{26}$ erg s$^{-1}$ Hz$^{-1}$ | $V^{c}$ |
|-------------|-------------|-----------------------------|-----------------------------|-----------------------------|----------------------------------|--------------|
| A0          | SN          | 33.6212                    | 46.707                      | 318 ± 42                    | 446 ± 33                         | 7.9 ± 1.0    | 11.1 ± 0.8 | 2.4  |
| A1          | SNR         | 33.6199                    | 46.699                      | 855 ± 58                    | 901 ± 51                         | 21.3 ± 1.4   | 22.4 ± 1.3 | 0.6  |
| A2          | SNR         | 33.6219                    | 46.655                      | 708 ± 53                    | 713 ± 43                         | 17.6 ± 1.3   | 17.7 ± 1.1 | 0.1  |
| A3          | SNR         | 33.5942                    | 46.560                      | 398 ± 44                    | 353 ± 30                         | 9.9 ± 1.1    | 8.8 ± 0.7 | 0.8  |
| A4          | SNR         | 33.6501                    | 46.537                      | 558 ± 48                    | 628 ± 40                         | 13.9 ± 1.2   | 15.6 ± 1.0 | 1.1  |
| A5          | SN?         | 33.6176                    | 46.693                      | 278 ± 41                    | 143 ± 25                         | 6.9 ± 1.0    | 3.6 ± 0.6 | 2.8  |
| A6          | SN          | 33.6206                    | 46.597                      | 208 ± 40                    | ≤72                              | 5.2 ± 1.0    | ≤1.8      | 3.4  |
| A7          | SNR         | 33.6300                    | 46.786                      | 496 ± 46                    | 468 ± 34                         | 12.3 ± 1.2   | 11.6 ± 0.8 | 0.5  |
| A8          | SNR         | 33.6306                    | 46.401                      | 226 ± 41                    | 264 ± 27                         | 5.6 ± 1.0    | 6.6 ± 0.7 | 0.8  |
| A9          | SNR         | 33.6306                    | 46.620                      | 294 ± 42                    | 282 ± 28                         | 7.3 ± 1.0    | 7.0 ± 0.7 | 0.2  |
| A10         | SNR         | 33.6392                    | 46.551                      | 550 ± 48                    | 436 ± 32                         | 13.7 ± 1.2   | 10.9 ± 0.8 | 2.0  |
| A11         | SNR         | 33.6403                    | 46.583                      | 300 ± 42                    | 351 ± 30                         | 7.5 ± 1.0    | 8.7 ± 0.7 | 1.0  |
| A12         | SN          | 33.6495                    | 46.590                      | 449 ± 45                    | 639 ± 40                         | 11.2 ± 1.1   | 15.9 ± 1.0 | 3.2  |
| A13         | SN?         | 33.6531                    | 46.733                      | 251 ± 41                    | 118 ± 25                         | 6.2 ± 1.0    | 2.9 ± 0.6 | 2.8  |
| A14         | SNR         | 33.6825                    | 46.571                      | 292 ± 42                    | 260 ± 27                         | 7.3 ± 1.0    | 6.5 ± 0.7 | 0.6  |
| A15         | SN          | 33.5991                    | 46.638                      | 159 ± 40                    | 304 ± 28                         | 4.0 ± 1.0    | 7.6 ± 0.7 | 3.0  |
| A16         | uncl.       | 33.6149                    | 46.516                      | ≤117                        | 147 ± 25                         | ≤2.9         | 3.7 ± 0.6 | 1.2  |
| A17         | uncl.       | 33.6179                    | 46.561                      | ≤117                        | 179 ± 26                         | ≤2.9         | 4.5 ± 0.6 | 2.4  |
| A18         | uncl.       | 33.6192                    | 46.464                      | 151 ± 40                    | 129 ± 25                         | 3.8 ± 1.0    | 3.2 ± 0.6 | 0.5  |
| A19         | SN?         | 33.6186                    | 46.659                      | ≤117                        | 191 ± 26                         | ≤2.9         | 4.8 ± 0.6 | 2.8  |
| A20         | uncl.       | 33.6278                    | 46.789                      | ≤117                        | 146 ± 25                         | ≤2.9         | 3.6 ± 0.6 | 1.2  |
| A21         | uncl.       | 33.6291                    | 46.836                      | ≤117                        | 133 ± 25                         | ≤2.9         | 3.3 ± 0.6 | 0.6  |
| A22         | uncl.       | 33.6354                    | 46.678                      | 173 ± 40                    | 217 ± 26                         | 4.3 ± 1.0    | 5.4 ± 0.7 | 0.9  |
| A23         | uncl.       | 33.6360                    | 46.560                      | ≤117                        | 137 ± 25                         | ≤2.9         | 3.4 ± 0.6 | 0.8  |
| A24         | uncl.       | 33.6361                    | 46.764                      | ≤117                        | 166 ± 25                         | ≤2.9         | 4.1 ± 0.6 | 2.0  |
| A25         | SN?         | 33.6524                    | 46.701                      | 132 ± 40                    | 209 ± 26                         | 3.3 ± 1.0    | 5.2 ± 0.7 | 1.6  |

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*a Coordinates are given with respect to $\alpha$(J2000.0) = 11:28:00.0000 and $\delta$(J2000.0) = 58:33:00.000, and were obtained from the 5 December 2008 image. The positions of those sources also detected in 8 April 2008 coincide within the errors ($\leq$0.5 mas) with all of them.

*b The uncertainty in the reported flux density for the detected compact components corresponds to 1σ, where σ was determined by adding in quadrature the off-source rms in each image and a 5% of the local maxima, to conservatively account for possible inaccuracies in the eEVN calibration.

*c We define the significance of the flux density variability between the two consecutive epochs as $V = |S_{Dec} - S_{Apr}| / \sqrt{\sigma_{Dec}^2 + \sigma_{Apr}^2}$, where $S_{Apr}$ and $S_{Dec}$ (S$_{Dec}$ and S$_{Apr}$) are the values inCols. 5 and 6 (7 and 8), respectively.

*d Source names are given in right ascension order, except for the five components reported previously (A0 through A4) by (Neff et al. 2004).
Table 2. Brightness temperatures\(^a\) of the VLBI sources in Arp 299-A.

| Source name | \(S_\nu \, (\mu\text{Jy})\) | \(a\) (mas) | \(b\) (mas) | \(T_B\) (K) | \(S_\nu \, (\mu\text{Jy})\) | \(a\) (mas) | \(b\) (mas) | \(T_B\) (K) |
|-------------|-----------------|-----------|-----------|----------|-----------------|-----------|-----------|----------|
| A0          | 318 ± 42        | ≤2.8      | ...       | ...      | 446 ± 33         | 5.3       | 3.0       | 1.8 × 10^6 |
| A1          | 855 ± 58        | ≤3.6      | ...       | ...      | 901 ± 51         | 2.1       | 1.8       | 1.6 × 10^7 |
| A2          | 708 ± 53        | ≤2.5      | ≤1.5      | ≥1.3 × 10^7 | 713 ± 43         | 2.1       | 1.6       | 1.4 × 10^7 |
| A3          | 398 ± 44        | ≤3.2      | ...       | ...      | 353 ± 30         | ≤6.5      | ≤0.3      | ≥1.2 × 10^7 |
| A4          | 558 ± 48        | ≤3.6      | ≤2.3      | ≥1.0 × 10^6 | 628 ± 40         | ≤2.8      | ≤0.5      | ≥3.0 × 10^7 |
| A5          | 278 ± 41        | ≤11.1     | ≤1.2      | ≥1.3 × 10^6 | 143 ± 25         | ...       | ...       | ...       |
| A6          | 208 ± 40        | ≤7.6      | ≤1.4      | ≥1.3 × 10^6 | ≤72              | ...       | ...       | ...       |
| A7          | 496 ± 46        | ≤2.5      | ≤3.3      | ≥4.0 × 10^6 | 468 ± 34         | 3.4       | 2.0       | 4.6 × 10^6 |
| A8          | 226 ± 41        | ≤4.8      | ...       | ...      | 264 ± 27         | ≤3.3      | ≤0.7      | ≥7.6 × 10^7 |
| A9          | 294 ± 42        | ≤3.6      | ≤4.4      | ≥1.2 × 10^6 | 282 ± 28         | ...       | ...       | ...       |
| A10         | 550 ± 48        | ≤3.2      | ≤3.9      | ≥2.9 × 10^6 | 436 ± 32         | ...       | ...       | ...       |
| A11         | 300 ± 42        | ≤5.5      | ...       | ...      | 351 ± 30         | ≤4.5      | ≤1.8      | ≥2.0 × 10^6 |
| A12         | 449 ± 45        | ≤3.1      | ≤3.7      | ≥2.6 × 10^6 | 639 ± 40         | 2.3       | 1.5       | ≤1.2 × 10^7 |
| A13         | 251 ± 41        | ≤3.3      | ≤4.2      | ≥1.2 × 10^6 | 118 ± 25         | ≤5.3      | ...       | ...       |
| A14         | 292 ± 42        | ≤5.0      | ≤3.7      | ≥1.1 × 10^6 | 260 ± 27         | ≤4.9      | ...       | ...       |
| A15         | 159 ± 40        | ...       | ...       | ...      | 304 ± 28         | ≤2.8      | ≤1.6      | ≥4.5 × 10^6 |
| A16         | ≤117            | ...       | ...       | ...      | 147 ± 25         | 5.6       | 3.2       | 5.5 × 10^5 |
| A17         | ≤117            | ...       | ...       | ...      | 179 ± 26         | 7.3       | 3.9       | 4.2 × 10^5 |
| A18         | 151 ± 40        | ...       | ...       | ...      | 129 ± 25         | ≤5.1      | ≤5.5      | ≥3.1 × 10^5 |
| A19         | ≤117            | ...       | ...       | ...      | 191 ± 26         | ≤4.0      | ≤2.0      | ≥1.6 × 10^6 |
| A20         | ≤117            | ...       | ...       | ...      | 146 ± 25         | ≤7.9      | ≤3.5      | ≥3.5 × 10^6 |
| A21         | ≤117            | ...       | ...       | ...      | 133 ± 25         | ≤7.4      | ≤2.9      | ≥4.1 × 10^6 |
| A22         | 173 ± 40        | ...       | ...       | ...      | 217 ± 26         | ≥8.6      | ≥4.3      | ≥3.9 × 10^6 |
| A23         | ≤117            | ...       | ...       | ...      | 137 ± 25         | ≥8.8      | ≤2.9      | ≥3.6 × 10^6 |
| A24         | ≤117            | ...       | ...       | ...      | 166 ± 25         | ≥8.6      | ≤7.0      | ≥1.8 × 10^6 |
| A25         | 132 ± 40        | ...       | ...       | ...      | 209 ± 26         | ≥8.6      | ≤4.4      | ≥3.7 × 10^5 |

\(^a\) The brightness temperatures shown for the 5.0 GHz VLBI source components in Arp 299-A were calculated using the flux densities in Table 1 and the angular sizes quoted here. We derived the brightness temperatures from the general formula: \(T_B = (2c^2/k) B_\nu \nu^{-2}\), where \(B_\nu\) is the intensity, in erg s\(^{-1}\) Hz\(^{-1}\) str\(^{-1}\). Since \(B_\nu\) depends on the measured flux density, \(S_\nu\), and on the deconvolved angular size of each VLBI component (obtained by fitting them to elliptical Gaussians, characterized by their major and minor semi-axis, \(a\) and \(b\)). Therefore, the above formula can be rewritten as \(T_B = (2c^2/k) B_\nu \nu^{-2} S_\nu a^{-1} b^{-1}\), where \(S_\nu\) is in mJy, \(\nu\) in GHz, and \(a\) and \(b\) are in milliarcseconds, respectively.
Appendix A: eEVN observations of Arp 299-A

A.1. Observing strategy

We observed the central regions of Arp 299-A at a frequency of 5 GHz in two epochs using the EVN. Our first epoch of 8–9 April 2008 (2008.99; experiment code RP009) included the following six antennas (acronym, diameter, location): Cambridge (CM, 32 m, United Kingdom), Medicina (MC, 32 m, Italy), Jodrell Bank (JB, 76 m, United Kingdom), Onsala (ON, 25 m, Sweden), Torun (TO, 32 m, Poland), and Westerbork array (WB, 25 m, The Netherlands). Our second observing epoch on 5 December 2008 (2008.340; RP014A experiment) included, in addition the EVN antennas Effelsberg (EF, 100 m, Germany), Knockin (KN, 25 m, United Kingdom), and Shanghai (SH, 25 m, China).

Both observing epochs consisted of e-VLBI phase-referenced experiments, using a data recording rate of 512 Mbps with two-bit sampling, for a total bandwidth of 64 MHz. The data were correlated at the EVN MkIV data processor at JIVE using an averaging time of 1 s. First epoch observations consisted of ~8.0 h on target. The telescope systems recorded both right-hand and left-hand circular polarization (LCP and RCP), which, after correlation, were combined to obtain the total intensity mages presented in this paper. Scans of 4.5 min for our target source, Arp 299-A, were alternated with 2 min scans of our phase reference source, J1128+5925. Both 3C 345 and 4C 39.25 were used as fringe finders and bandpass calibrators. Our second epoch consisted of ~4.5 h on target. The telescope systems also recorded data in dual polarization mode, and 4.5 min on-source scans were alternated with 1 min scans of J1128+5925. The bright sources 3C 84, 3C 138, 4C 39.25, and 3C 286 were used as fringe finders and band-pass calibrators. We note that the inclusion of EF in the second observing epoch allowed us to achieve a much lower rms, in spite of the significantly smaller amount of total observing time.

A.2. Data calibration and imaging

We analyzed the correlated data for each epoch using the NRAO Astronomical Image Processing System (AIPS). The visibility amplitudes were calibrated using the system temperature and gain information provided for each telescope. Standard inspection and editing of the data were done within AIPS. The bandpasses were corrected using the bright calibrator 4C 39.25. We applied standard corrections to the phases of the sources in our experiment, including ionosphere corrections (using the total electron content measurements publicly available).

Because of the limited bandwidth of CM and KN, the usable data acquired by these antennas was found in a single subband with very noisy edges. To improve the quality of the bandpass calibration, we removed the edges of CM for the first epoch, and the edges of CM and KN for the second epoch. The instrumental phase and delay offsets among the 8-MHz baseband converters in each antenna were corrected using a phase calibration determined from observations of 4C 39.25. The data for the calibrator J1128+5925 were then fringe-fitted in a standard manner. We then exported the J1128+5925 data from AIPS into the Caltech imaging program DIFMAP (Shepherd et al. 1995) for mapping purposes. In this way, we determined gain correction factors for each antenna. J1128+5925 showed a flux of ~0.38 Jy at 5.0 GHz at both epochs, and displayed a point-like structure on mas scales. After this procedure was completed within DIFMAP, the data were read back into AIPS, where the gain corrections determined by DIFMAP were applied to the data.

The final source model obtained for J1128+5925 was then included as an input model in a new fringe-fitting search for J1128+5925, thus removing the structural phase contribution to the solutions of the delay and fringe rate for our target source, Arp 299-A, prior to obtaining the final eEVN images shown in Fig. 1. The phases, delays, and delay-rates determined for J1128+5925 were then interpolated and applied to the source Arp 299-A. This procedure allowed us to obtain the maximum possible accuracy in the positions reported for the compact components in Fig. 1. We note, however, that this has no impact on the final images, since J1128+5925 is essentially point-like at the angular resolution (~50 mas) provided by our 5.0 GHz e-EVN observations, and its phase-contribution is therefore negligible.

The imaging and deconvolution of Arp 299-A was performed with the AIPS task IMAGR (see Figs. 1 and A.1), using a natural weighting scheme and a ROBUST parameter equal to zero. This scheme was a good compromise when maximizing the very high angular resolution and very low rms values in our images. We point out that we kept the averaging integration time to 1 s and used a maximum channel bandwidth in the imaging process of 8 MHz, which results in a maximum degradation of the peak response for the component furthest away from the phase center of less than 5% and prevents artificial smearing of the images (e.g., Bridle & Schwab 1999).

No self-calibration of the phases, nor of the amplitudes, was performed on the data, since the peaks of emission were very faint in these procedures. We emphasize two important aspects of the phase-reference technique: (i) it effectively increases the
on-source integration time from minutes to hours, thus significantly increasing the array sensitivity, and allowing the detection and imaging of very faint objects (Beasley & Conway 1995) and (ii) it retains the positional information about the compact components in Arp 299-A with respect to the phase-reference source J1128+5925, which lies 0.86° from the target source.

A.3. Source detection, identification, and flux density extraction

Our 5.0 GHz eEVN observations on 8 April 2008 and 5 December 2008 resulted in off-source rms noises of 39 μJy/b and 24 μJy/b, respectively. The difference in sensitivity was primarily due to the addition of the Effelsberg antenna in our second observing epoch, but also to there being more antennas than in our first epoch. We considered as real sources individual peaks with a signal-to-noise ratio equal to, or above five times the rms noise in either of our two observing epochs. Since our second observing epoch involved far more sensitive observations than the first one, this resulted in a larger number of detections of compact components (26) with respect to the first epoch (15).

We placed small boxes across the 8 April 2008 image, around the positions of those components detected on 5 December 2008, to extract the flux density of the counterparts initially detected only in the second epoch (components A15 through to A25 in Fig. 1). This procedure allowed us to recover four components above 3σ (A15, A18, A22, and A25), based on a positional coincidence with the peak of emission in our second epoch of greater precision than 0.5 milliarcsec; and for those components not detected on 8 April, to derive 3σ upper limits to the emission.

The flux density extraction was carried out within AIPS, using task IMFIT, which fits Gaussian components to the image. Namely, we placed small boxes (corresponding to the few inner pixels of each source) around each local peak of brightness (above five times the rms noise) and fitted single Gaussian components to each of them. Since the fitted integrated flux densities differed insignificantly from the peaks of emission (by less than 1%), it is clear that there is no evidence that any of the compact components are resolved even with the very high angular resolution of a few milliarcsec that the eEVN delivers. The total flux densities listed in Table 1 are thus the peak flux densities found in our images.