Digging deep into the ULIRG phenomenon: When radio beats dust

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Abstract

Luminous and Ultra-Luminous Infrared Galaxies (U/LIRGs) do also radiate copious amounts of radio emission, both thermal (free-free) and non-thermal (mainly synchrotron). This is very handy since, unlike optical and infra-red observations, radio is not obscured by the ubiquitous dust present in U/LIRGs, which allows a direct view of the ongoing activity in the hearts of those prolific star-forming galaxies. Here, I first justify the need for this high-angular resolution radio studies of local U/LIRGs, discuss the energy budget and the magnetic field, as well as IC and synchrotron losses in U/LIRGs, and present some selected results obtained by our team on high-angular resolution radio continuum studies of U/LIRGs. Among other results, I show the impressive discovery of an extremely prolific supernova factory in the central $\sim$150 pc of the galaxy Arp 299-A ($D = 45$ Mpc) and the monitoring of a large number of very compact radio sources in it, the detection and precise location of the long-sought AGN in Arp 299-A. A movie summarizing those results can be found in http://www.iaa.es/ torres/research/arp299a.html. All those results demonstrate that very-high angular resolution studies of nearby U/LIRGs are of high relevance for the comprehension of both local and high-z starbursting galaxies.

1   Introduction

The study of galaxies at the highest infrared luminosities, i.e., Luminous $10^{11}\,\mathrm{L_\odot} \leq \mathrm{L_{IR}} \leq 10^{12}\,\mathrm{L_\odot}$) and Ultra-Luminous ($\mathrm{L_{IR}} \geq 10^{12}\,\mathrm{L_\odot}$) Infrared Galaxies (LIRGs and ULIRGs, respectively) is relevant for many reasons:

- U/LIRGs account for about 10% of the total radiant energy production and $\sim 20\%$ of all the high-mass star-formation in the local universe (e.g., [5]).

- The bulk of the energy radiated by ULIRGs is infrared emission from warm dust grains heated by a central power source, or sources, whose nature (AGN, starburst, or both) is often unknown, but whose evolution is likely to be related.

- Essentially all LIRGs above $\sim 10^{11.4}\,\mathrm{L_\odot}$ appear to be interacting galaxies, and all ULIRGs seem to be advanced merger systems. Thus they may represent an important stage in the formation of quasi-stellar objects.

- U/LIRGs are also of cosmological relevance, as they bear many similarities with star-forming galaxies at high-z (e.g. local UV-bright starbursts are good analogs to Lyman Break Galaxies (e.g. [18]).

- Finally, U/LIRGs are ideal laboratories to study the complex ecosystems of stars, gas, Black Holes, the interstellar medium (ISM), and test massive star and black-hole/starburst evolution, or probe the Initial Mass Function (IMF) of the high-mass stars.

2   The dust heating central source: AGN vs. SB

The critical question concerning U/LIRGs is whether the dust in the central regions ($r \lesssim 1\,\mathrm{kpc}$) is heated by a starburst or an active galactic nucleus (AGN), or a combination of both. Mid-infrared spectroscopic studies on samples of ULIRGs suggested that the vast majority of these galaxies were powered predominantly by recently formed massive stars, with a significant heating from the AGN only in the most luminous objects [33]. These authors also found that at least half of ULIRGs are probably powered by both an AGN and a starburst in a circumnuclear disk or ring. These circumnuclear regions are typically located at radii $r \lesssim 700\,\mathrm{pc}$ from the nucleus of the galaxy, and also contain large quantities of dust. Those facts (compactness of the emission and dusty environments) prevent to gain much insight into the nature of the central source, either from optical, or infrared observations.

Why radio observations? The largely dusty environments of U/LIRGs imply huge extinctions in the optical, and even in the infrared, which prevents the direct detection of recent starburst activity, e.g., via supernova explosions. The advantage of observing in radio is that these wavelengths are not affected by dust obscuration, thus allowing to see the activity within those deeply buried regions.

Why high-angular resolution? At a typical distance of 100 Mpc to a local U/LIRG, 1" corresponds to a linear size of about 500 pc. Therefore, if one aims at spatially resolving the circumnuclear regions of U/LIRGs to understand in detail the ongoing processes in the central regions of those monsters, sub-arcsecond resolution is a must. This makes an excellent case for high-angular resolution radio observations of U/LIRGs, since current radio interferometric arrays provide sub-arcsecond angular resolution (EVLA, MERLIN) or even milliarcsecond resolution, using Very Long Baseline Interferometry (VLBI).

How do U/LIRGs look in radio? The central kiloparsec region of many nearby U/LIRGs shows a distribution of their radio emission typically consisting of a compact ($\lesssim 200\,\mathrm{pc}$), high surface brightness, central radio source corresponding to an active nuclear region (whether powered by an AGN, or a nuclear starburst), immersed in a low surface brightness circumnuclear, extended ($\simeq 1\,\mathrm{kpc}$) halo [8].

As an example, I show in Fig. 1 an 8.46 GHz VLA image of the LIRG Mrk 331. At

a distance of $D = 75$ Mpc to Mrk 331, $1''$ corresponds to a linear size of 357 pc. Note that all radio emission is concentrated in a region whose angular size is less that $3''$ in diameter, or less than 1 kpc. The total 8.5 GHz flux density is of $\simeq 29.3$ mJy, corresponding to a monochromatic radio luminosity of $\sim 1.6 \times 10^{29}$ erg s^{-1} Hz^{-1}.

Often, the high-surface brightness is not within the central $\sim$200 pc region, but on a prominent circumnuclear ring where a burst of recent star formation is ongoing. Fig. 2 shows an 8.46 GHz VLA image of the LIRG NGC 1614. At the distance of $D =$65.6 Mpc to NGC 1614, $1''$ corresponds to a linear size of 320 pc. As with Mrk 331, all radio emission is concentrated in a region less than 1 kpc in size. The total 8.5 GHz flux density is of $\simeq 32.9$ mJy, corresponding to a monochromatic radio luminosity of $\sim 1.8 \times 10^{29}$ erg s^{-1} Hz^{-1}, and I note that unlike the case of Mrk 331, where the circumnuclear ring is very faint, about 90% of the radio luminosity from NGC 1614 comes from a prominent circumnuclear ring which is at a distance of $\sim$250 pc from the nucleus of the galaxy.

Based on those high-angular radio observations, it is evident that, contrary to what we could have thought from a look at a low-angular resolution image, most of the starburst activity happening in NGC 1614 is actually taking place in this ring. By converting the measured flux density into a brightness temperature, $T_{\rm b}$, we would find out that this temperature is, in most regions of the ring, much higher than the thermal temperature of the plasma around the massive stars, implying a non-thermal (synchrotron) origin for the radio emission. The natural explanation for this non-thermal emission is that it is due to recent explosions of core-collapse supernovae (CCSNe) and supernova remnants (SNRs), which implies that most of the starburst activity is still ongoing ($t \lesssim 40$ Myr) in the ring of NGC 1614.

3   Radio as a direct tracer of massive star-formation in U/LIRGs

A large fraction of the massive star-formation at both low- and high-z has taken place in U/LIRGs [16]. Indeed, by applying evolutionary stellar models to bursts of age $10-100$ Myr, and adopting a standard IMF, one can obtain the SFR as a function of $L_{\rm FIR}$ [15]:

$$\mathrm{SFR} \approx 17.2 \left(\frac{\mathrm{L_{FIR}}}{10^{11}\,\mathrm{L_\odot}} \right) \mathrm{M_\odot\,yr^{-1}} \tag{1}$$

While the compact, centrally located radio emission in these galaxies might be generated by a point-like source (AGN), or by the combined effect of multiple RSNe and supernova remnants (SNRs), e.g., the evolved nuclear starburst in Arp 220 ([23] and references therein) and M 82 (e.g. [20]), it seems now well established that in the circumnuclear regions of those objects there is an ongoing burst of star formation producing core-collapse supernovae (CCSNe, Type Ib/c and Type II SNe) at a high rate (e.g. NGC 7469, [9]; Arp 299, [21]; NGC 6240, [11]; Arp 220, [23]; IRAS 18293-3413, [17, 24]; IRAS 17138-1017, [14, 25, 13]).Therefore, a powerful tracer for (recent) starburst activity in U/LIRGs is the detection of CCSNe.

Since stars more massive than M $\gtrsim 8$ M$_\odot$ explode as CCSNe, the observed rate at which those stars die ($r_{\rm CCSN}$) can be used as a direct measurement of the current star formation rate (SFR) in galaxies, and may provide unique information about the initial mass function
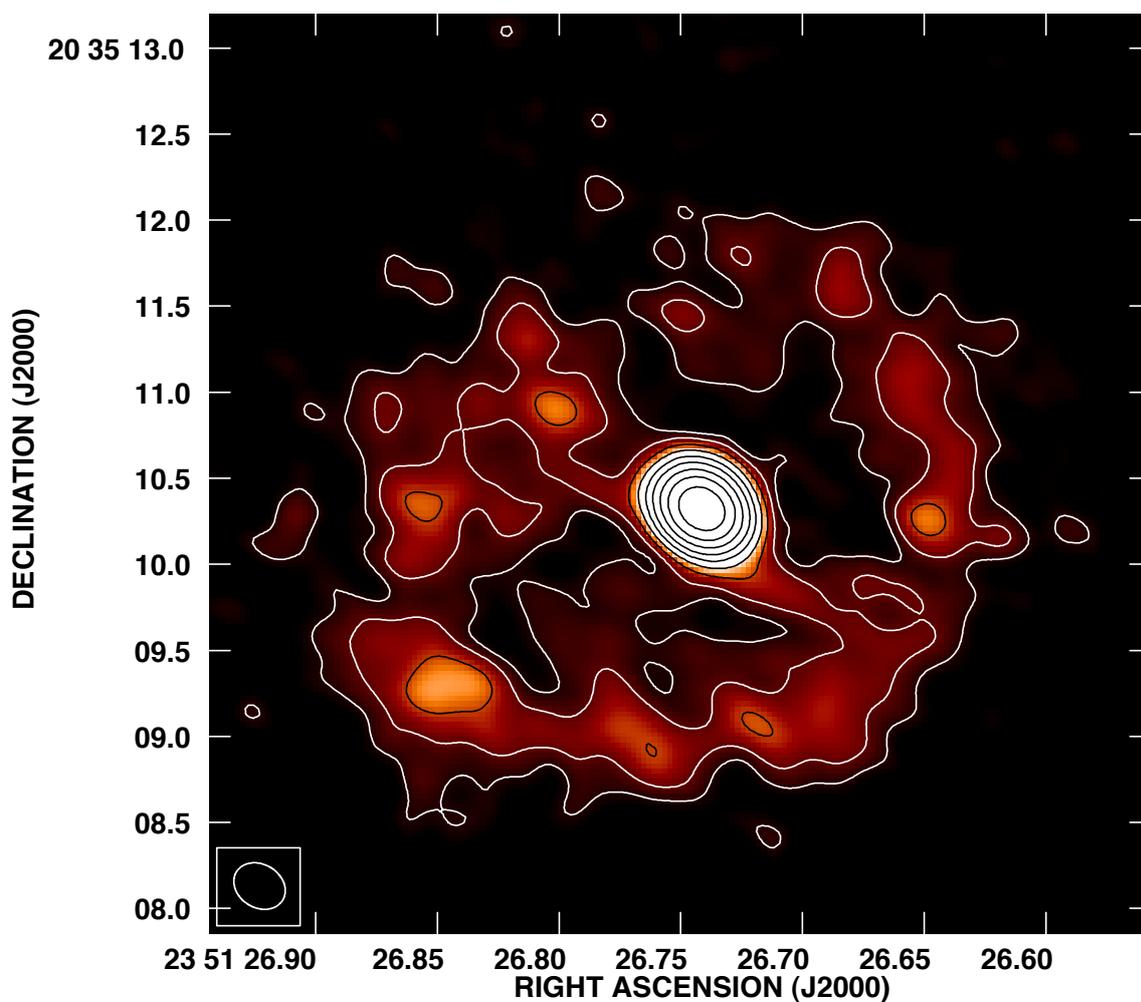
Figure 1:   The LIRG Mrk 331 ($D = 75$ Mpc) imaged at 8.46 GHz with the VLA on December 2006 (unpublished image). The synthesized FWHM beam is a Gaussian beam of size 0.27" × 0.25". Contour levels are drawn at $(3,3\sqrt{3},9,...)\times 19$ μJy beam^{-1}, the off-source rms of the image, and the peak of brightness is 7.3 mJy beam^{-1}, and corresponds to the bright spot in the central region of the galaxy. 1″corresponds to 357 pc. (See text for details.)
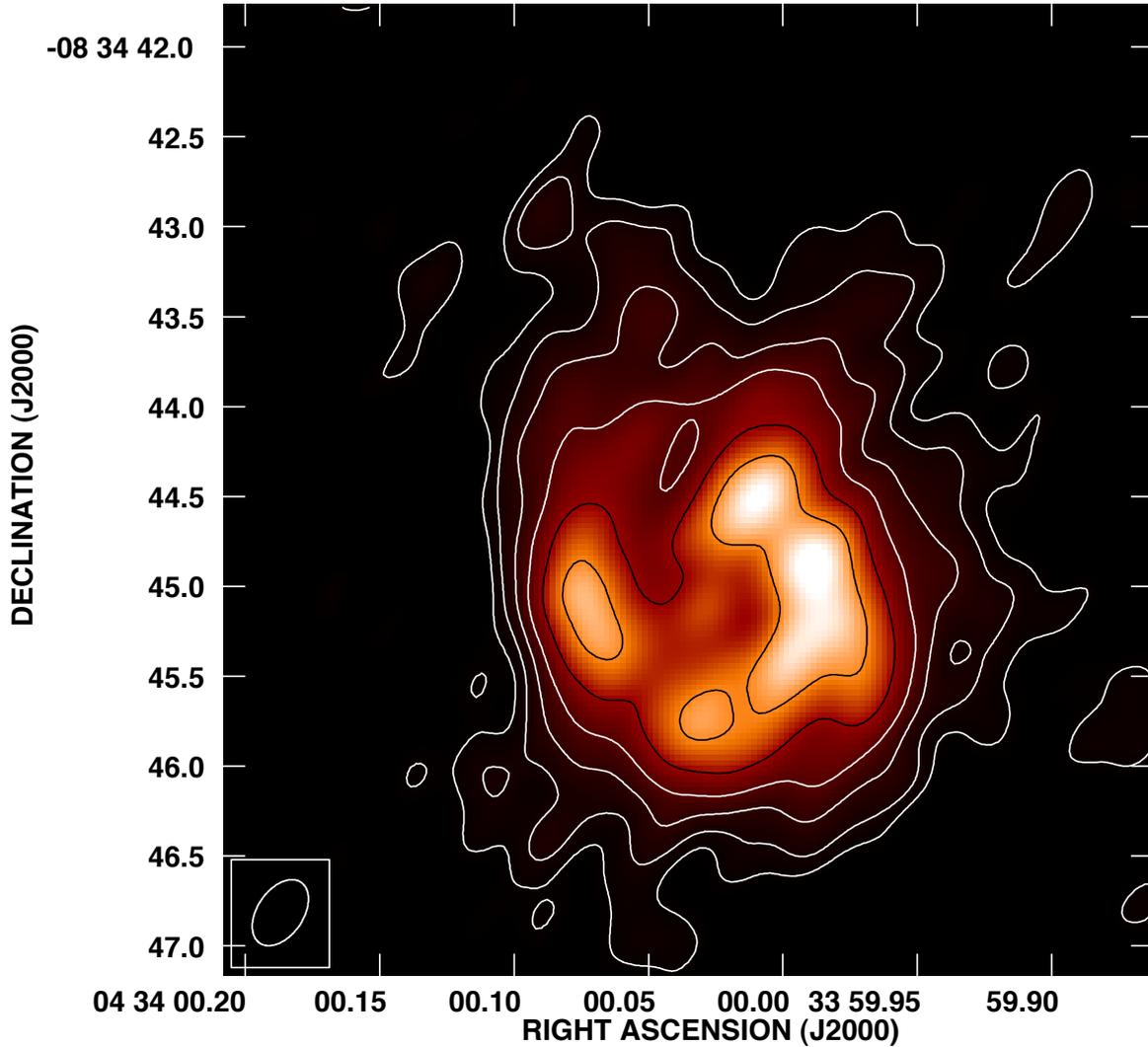
Figure 2: The LIRG NGC 1614 ($D = 65.6$ Mpc) imaged at 8.46 GHz with the VLA on June 2006 (unpublished image). The synthesized FWHM beam is a Gaussian beam of size 0.42" $\times$ 0.24". Contour levels are drawn at $(3, 3\sqrt{3}, 9, ...) \times 22$ μJy beam^{-1}, the off-source rms of the image, and the peak of brightness is 1.78 mJy beam^{-1}, and corresponds to a bright spot in the circumnuclear ring of star-formation. 1″corresponds to 320 pc. (See text for details.)

(IMF) of the high-mass stars. Indeed, if for the sake of simplicity we assume a constant star-formation rate for a starburst, it can be shown that (e.g. [26])

$$r_{\mathrm{CCSN}} = SFR \left(\frac{\alpha - 2}{\alpha - 1}\right) \left(\frac{m_{\mathrm{SN}}^{1-\alpha} - m_u^{1-\alpha}}{m_l^{2-\alpha} - m_u^{2-\alpha}}\right) \tag{2}$$

where SFR is the constant star formation rate in $\mathrm{M_\odot\,yr^{-1}}$, m_l and m_u are the lower and upper mass limits of the initial mass function (IMF, $\Phi \propto m^{-\alpha}$), and m_{SN} is the minimum mass of stars that yield supernovae, assumed to be 8 $\mathrm{M_\odot}$(e.g., [31]).

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$50 yr), the CCSN rate in U/LIRGs is expected to be at least one to two orders of magnitude higher than in normal galaxies, and hence detections of SNe in U/LIRGs offer a promising way of determining the current star formation rate in nearby galaxies. In fact, from Eq. 1, and assuming a Salpeter IMF ($\alpha = 2.35$) with $m_u = 100$ $\mathrm{M_\odot}$ and $m_l = 0.2$ $\mathrm{M_\odot}$, we obtain that a LIRG (ULIRG) is expected to yield about 0.26 (2.6) SN/yr, or more. Thus, Eqs. 1 and 2 imply that U/LIRGs are prolific star-forming factories, with LIRGs having typical values of SFRs and core-collapse supernova rates of $\sim$(17−170) $\mathrm{M_\odot\,yr^{-1}}$ and $r_{\mathrm{CCSN}} \sim$(0.3−3.0) $\mathrm{yr^{-1}}$, respectively, with ULIRGs exceeding those upper ends.

However, the direct detection of CCSNe in the extreme densities of the central few hundred pc of U/LIRGs is, as pointed out earlier, 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 a lower limit to the true value of r_{CCSN}. Fortunately, radio is not affected by dust absorption. Moreover, significant radio emission from CCSNe is expected –as opposed to thermonuclear SNe– as the interaction of the SN ejecta with the circumstellar medium (CSM) gives rise to a high-energy density shell, which is Rayleigh-Taylor unstable and drives turbulent motions that amplify the existing magnetic field in the presupernova wind, and efficiently accelerate relativistic electrons, thus enhancing the emission of synchrotron radiation at radio wavelengths [6].

Thus, starburst activity in the circumnuclear regions of LIRGs ensures both the presence of a high number of massive stars and a dense surrounding medium, so bright radio SNe are expected to occur. Those SNe can be detected, even 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 unveil nuclear starbursts and detect individual radio supernovae at large distances in the local Universe (e.g. Arp 220, [23];Arp 299, [26, 4]; see also Fig. 4.1; IC 883 [30]).

4 The local luminous infra-red galaxy Arp 299 as a case study

4.1 An extremely prolific supernova factory in Arp 299

Arp 299 consists of two interacting galaxies (IC 694 and NGC 3690), which are in an early merger stage. At a luminosity distance of 44.8 Mpc [10] for $H_0 = 73$ km s^{-1} Mpc^{-1}, Arp 299 has an infrared luminosity $L_{IR} \approx 6.7 \times 10^{11} L_\odot$, which almost qualifies it as a ULIRG. The innermost $\sim$150 pc nuclear region of Arp 299-A (see top left panel in Fig. 4.1) 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.

The brightest component at infrared and radio wavelengths is IC 694 (A in the top panel of Fig. 4.1; hereafter Arp 299-A), which accounts for $\sim$50% of the total infrared luminosity of the system [2], and $\sim$70% of its 5 GHz radio emission [21]. 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 $\sim$10 Myr [2]. Given that IC 694 accounts for most of the infrared emission in Arp 299, it is the region that is most likely to contain new SNe [7]. Since optical and near-infrared observations are likely to miss a significant fraction of CCSNe in the innermost regions of Arp 299-A due to high values of extinction ($A_V \sim 34 - 40$ [1]) 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 [21], one of which (A0) was identified as a young SN.

4.2 The AGN-Starburst connection in Arp 299-A

As mentioned in Sect. 1, the dusty nuclear regions of luminous infra-red galaxies (LIRGs) are heated by either an intense burst of massive star formation, or an active galactic nucleus (AGN), or a combination of both. Disentangling the contribution of each of those putative dust-heating agents is a challenging task, and direct imaging of the innermost few pc can only be accomplished at radio wavelengths, using very high-angular resolution observations.

My team and I started to monitor the A-nucleus of the interacting starburst galaxy Arp 299, using very long baseline interferometry (VLBI) radio observations at 1.7 and 5.0 GHz [28]. Our aim was to characterize the compact sources in the innermost few pc region of Arp 299-A, as well as to detect recently exploded core-collapse supernovae. We imaged with milliarcsecond resolution the inner eight parsecs of the nuclear region in Arp 299-A, using contemporaneous EVN observations at 1.7 and 5.0 GHz [27], and the summary of those results is shown in the right panel of Fig. 4.1. At 5.0 GHz, we detect components A0, A1, and A5, as previously detected by [28]. At 1.7 GHz, A1 and A5 are also detected, but not A0. In addition, two new components between A1 and A5 (A1b and A1c) are detected at 1.7 GHz, forming a complex.
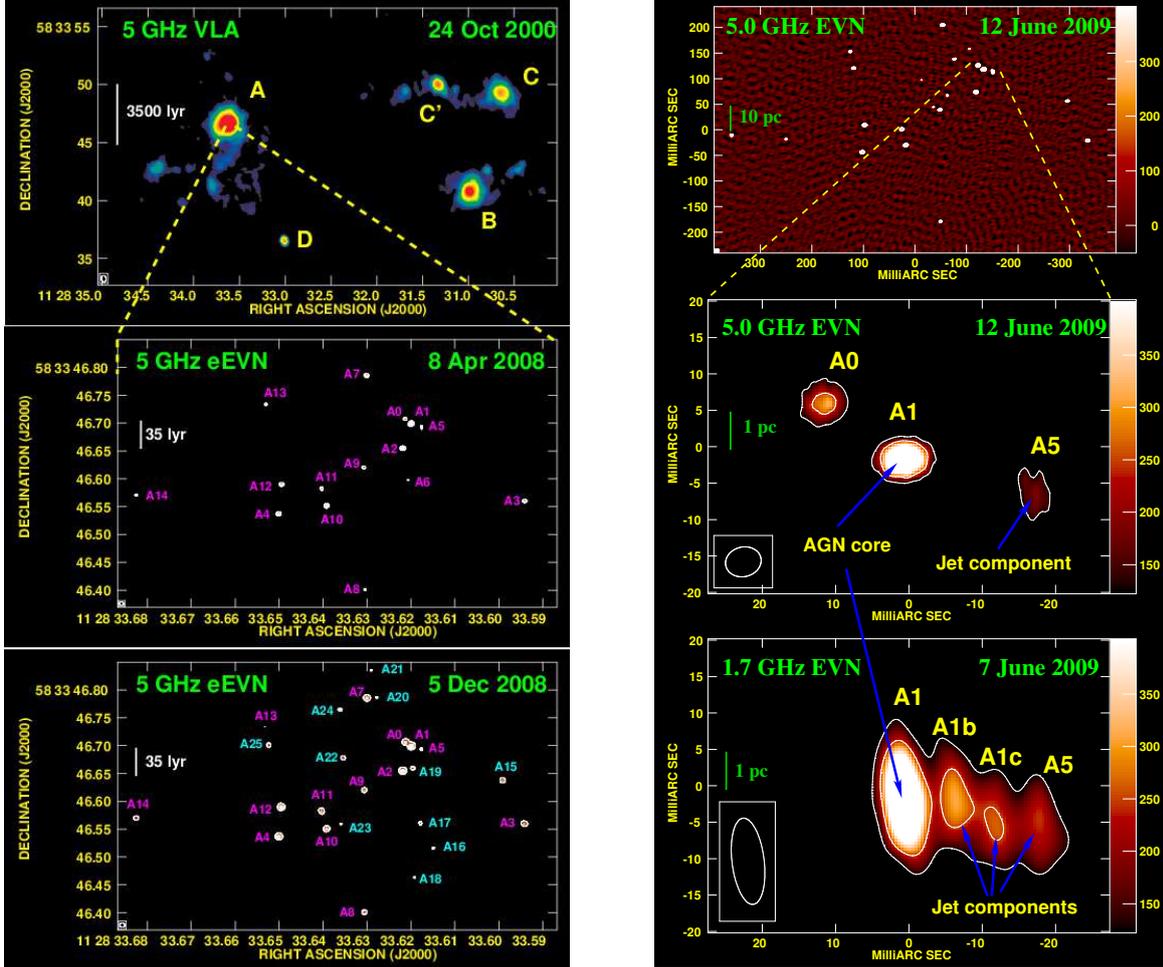
Figure 3:   *Top left panel:* 5 GHz VLA archival observations of Arp 299 on 24 October 2000, displaying the five brightest knots of radio emission in this merging galaxy. *Middle left and bottom left panels:* Contour maps drawn at five times the r.m.s. of our 5 GHz eEVN observations of the central 500 light years of the luminous infrared galaxy Arp 299-A on 8 April 2008 and 5 December 2008, revealing a large population of relatively bright, compact, non-thermal emitting sources. The size of the FWHM synthesized interferometric beam was (0.6 arcsec × 0.4 arcsec) for the VLA observations, and (7.3 milliarcsec × 6.3 milliarcsec) and (8.6 milliarcsec × 8.4 milliarcsec) for the EVN observations on 8 April 2008 and 5 December 2008, respectively. To guide the reader's eye, we show in cyan the components detected only at the 5 December 2008 epoch. *Top right panel:* 5.0 GHz full EVN image of the central 150 pc 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 left and bottom left panels:* Blow-ups of the inner 8 pc 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. Contours are drawn at 5 and 10 times the off-source r.m.s. noise.

The morphology, spectral index, radio luminosity, and radio-to-X ray luminosity ratio of the A1−A5 complex are consistent with that of an LLAGN, and rules out the possibility that it consists of a chain of young RSNe and SNRs in a young SSC. We therefore concluded that A1 is the long-sought AGN in Arp 299-A. Since Arp 299-A had long been thought of as a pure starburst, our finding of a buried, low-luminosity AGN in its central region, coexisting with a recent burst of starformation, suggests that both a starburst and AGN are frequently associated phenomena in mergers. In this case, our result is likely to have an impact on evolutionary scenarios proposed for AGN and the triggering mechanism of activity in general.

We note that component A0, previously identified as a young RSN by [21], is not seen at our low-frequency observations, which implies there must be a foreground absorbing H II region, which precludes its detections at frequencies $\lesssim 1.7$ GHz. It is remarkable that this RSN exploded at the mere (deprojected) 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. This result may also be relevant to accreting models in the central regions of galaxies, since it is not easy to explain the existence of very massive, supernova progenitor stars so close to an AGN. While seemingly contradictory, this could explain the low-luminosity of the AGN we see in Arp 299-A. In fact, since massive stars shed large amounts of mechanical energy into their surrounding medium, thereby significantly increasing its temperature, those massive stars would hinder the accretion of material to the central black hole, which could in turn result in a less powerful AGN than usual. (See also [12] and the contribution of Herrero-Illana et al. to these proceedings.)

5 Energy budget in U/LIRGs

Since essentially all of the observed radio emission in the central regions of U/LIRGs is of synchrotron origin (see Sect. 2.1), we can estimate a minimum total energy in magnetic fields, electrons, and heavy particles and a minimum magnetic field for them. In fact, if we assume equipartition (magnetic field energy is approximately equal to the total particle energy), then the minimum total energy is [22]

$$E_{\min}^{(\mathrm{tot})} = c_{13} \, (1+k)^{4/7} \, \phi^{3/7} \, R^{9/7} \, L^{4/7} \qquad (3)$$

where L is the radio luminosity of the source between ν_1 and ν_2, R is a characteristic size, c_{13} is a slowly-dependent function of the observed radio spectral index, α, ϕ is the fraction of the supernova's volume occupied by the magnetic field and by the relativistic particles (filling factor), and k is the ratio of the (total) heavy particle energy to the electron energy. This ratio depends on the mechanism that generates the relativistic electrons, ranging from $k \approx 1$ up to $k = m_p/m_e \approx 2000$, where m_p and m_e are the proton and electron mass, respectively. A value of $k \simeq 100$ seems appropriate for most galaxies [3]. For the sake of simplicity, I will use a value of $\alpha = -0.7$, which is a typical radio synchrotron spectral index. The value of the function c_{13} is $\sim 2.4 \times 10^4$ (for $\alpha = -0.7$, $\nu_1 = 30$ MHz and $\nu_2 = 30$ GHz). The characteristic size of the synchrotron emitting region in U/LIRGs varies from case to case, although the

most compact starbursts, typically residing in ULIRGs, i.e., advanced mergers, have sizes of $\sim$100–200 pc, and for the sake of simplicity we will use here a nominal value of $R = 100$ pc, and a filling factor value, $\phi = 0.5$. The total (synchrotron) radio luminosity between $\nu_1 = 30$ MHz and $\nu_2 = 30$ GHz (for $\alpha = -0.7$) can be written as

$$L_{\mathrm{R}} \approx 5 \times 10^{39} \left(\frac{S_{\nu,0}}{10\,\mathrm{mJy}} \right) \left(\frac{D}{100\,\mathrm{Mpc}} \right)^2 \mathrm{erg\,s}^{-1} \tag{4}$$

where $S_{\nu,0}$ is the flux density, in mJy, at a reference frequency. With these values, the minimum total energy, and its associated magnetic field, enclosed in a 100 pc region of a U/LIRG at a nominal distance of 100 Mpc with $S_{\nu,0}$=10 mJy are

$$E_{\mathrm{min}}^{(\mathrm{tot})} \approx 1.9 \times 10^{53}(1+k)^{4/7} \left(\frac{S_{\nu,0}}{10\,\mathrm{mJy}} \right)^{4/7} \left(\frac{\phi}{0.5} \right)^{3/7} \left(\frac{R}{100\,\mathrm{pc}} \right)^{9/7} \left(\frac{D}{100\,\mathrm{Mpc}} \right)^{14/7} \mathrm{erg} \tag{5}$$

$$B_{\mathrm{min}} \approx 128\,(1+k)^{2/7} \left(\frac{S_{\nu,0}}{10\,\mathrm{mJy}} \right)^{2/7} \left(\frac{\phi}{0.5} \right)^{-2/7} \left(\frac{R}{100\,\mathrm{pc}} \right)^{-6/7} \left(\frac{D}{100\,\mathrm{Mpc}} \right)^{4/7} \mu\mathrm{G} \tag{6}$$

where we have set $c_{12} = 10^7$ in the above equation, for simplicity. Since $1 \leq k \leq 2000$, $E_{\mathrm{min}}^{(\mathrm{tot})}$ is then between 2.8×10^{53} erg and 1.5×10^{55} erg, and equals 2.7×10^{54} erg for our nominal value of $k = 100$. The corresponding values of the equipartition magnetic field lie then between $\sim 156\,\mu$G (electrons dominate) and $\sim 1.1\,$mG (heavy particles dominate), and equals ~ 0.5 mG for our nominal value of $k = 100$. We see that the energy contained in the central, compact regions (size $\lesssim$ 100 pc) of U/LIRGs are huge, and the magnetic fields in those ambients are expected to be significant, since the above estimates are lower limits to the real values of the magnetic fields. Values of several hundreds of μG, or larger, have been obtained for the central regions of the ULIRGs IRAS 23365+3604 [29] and IRAS 17208$-$0014 [19], in agreement with the advanced-merger scenarios proposed for those ULIRGs.

6   Magnetic field and radiation field in U/LIRGs

We have just seen that the minimum equipartition total energy in the form of particles and magnetic field emitting by synchrotron radio emission within the central $\sim$100 pc of a U/LIRG is huge. In particular, the magnetic field is expected to be significantly larger than in normal galaxies, where on average has a value of $\sim 5\mu$G, and hence is expected to play a significant role in the physics of those objects. Similarly, since the bolometric luminosity of those beasts is dominated by radiative emission at IR wavelengths, it is also expected that the radiative field plays a significant role. *But which is the main player here: the radio synchrotron, or the radiative field?* In the previous Section, we obtained that a typical magnetic field for the central $\sim$100 pc of a U/LIRG is $\sim 500\,\mu$G (assuming $k \approx 100$). Therefore, we can write the energy density of the magnetic field as

$$U_{\mathrm{B}} = B^2/8\pi \approx 1.0 \times 10^{-8} \left(\frac{B}{500\mu\mathrm{G}}\right)^2 \mathrm{erg\,cm^{-3}} \tag{7}$$

Since the bolometric luminosity of U/LIRGs is dominated by the emission at infrared wavelengths, the energy density of the radiation field can then be written as

$$U_{\mathrm{rad}} \approx \frac{\mathrm{L_{ir}}}{c\,R^2} \approx 1.3 \times 10^{-7} \left(\frac{L_{\mathrm{ir}}}{10^{11}\,L_\odot}\right) \left(\frac{R}{100\,\mathrm{pc}}\right)^{-2} \mathrm{erg\,cm^{-3}} \tag{8}$$

Thus, *IC losses are likely to dominate the central ∼100 pc regions of U/LIRGs, if magnetic fields are close to minimum equipartition estimates.* We note, though, that it may well be that equipartition does not hold in those compact regions. For example, [32] suggest that minimum equipartition estimates are not reliable, if the nuclear disks in the central regions of U/LIRGs are magnetic field supported. In the former case, i.e., when the pressure of the magnetic field is large enough to compete with that of the gas in the nuclear disk, the implied magnetic fields would be high enough so that synchrotron losses would dominate over IC losses.

7 Summary

U/LIRGs are embedded in extremely dusty environments, which imply huge extinctions in the optical, and even in the infrared, thus preventing the direct detection of recent starburst activity, e.g., via supernova explosions. Radio is not affected by dust obscuration, thus allowing to see the activity within those deeply buried regions. In addition, at the typical distances of ∼100 Mpc to a local U/LIRG, sub-arcsecond angular resolution is mandatory to spatially resolve the circumnuclear regions of U/LIRGs, so as to understand in detail the ongoing processes in their central regions. Current radio interferometric arrays provide sub-arcsecond angular resolution (EVLA, MERLIN) or even milliarsecond resolution, using Very Long Baseline Interferometry (VLBI), and thus they become a very powerful tool to study U/LIRGs.

Here, I have presented some of the results obtained by our team, making use of high-angular resolution radio observations, including the impressive discovery of an extremely prolific supernova factory in the central ∼150 pc of the galaxy Arp 299-A ($D = 45$ Mpc) and the monitoring of a large number of very compact radio sources in it, or the detection and precise location of the long-sought AGN in Arp 299-A. In addition, VLBI observations of distant ULIRGs in the local universe have allowed us to estimate the energetics in magnetic fields and particles. The magnetic field estimates, of a few hundred μG within the ∼200 pc or so, are in agreement with evolutionary scenarios that suggest those ULIRGs are advanced mergers. More recently, we also used VLBI observations of to show evidence for the existence of nuclear disks ($\lesssim$ 100 pc in size) in starburst galaxies from their radial distribution of supernovae. All those results show that very-high angular resolution studies of nearby U/LIRGs are of high relevance for the comprehension of both local and high-z starforming galaxies.

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