A&A 553, A4 (2013)
DOI: 10.1051/0004-6361/201321089

Astronomy & Astrophysics

Radio continuum observations of the Leo Triplet at 2.64 GHz⋆

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Received 11 January 2013 / Accepted 14 March 2013

ABSTRACT

Context. The Leo Triplet group of galaxies is best known for the impressive bridges of neutral gas that connect its members. One of the bridges forms a large tidal tail extending eastwards from NGC 3628 that hosts several H I plumes and carries the material from this galaxy to the intergalactic space.

Aims. The magnetic fields of the member galaxies NGC 3628 and NGC 3627 show morphological peculiarities, suggesting that interactions within the group may be caused by stripping of the magnetic field. This process could supply the intergalactic space with magnetised material, a scenario considered as a possible source of intergalactic magnetic fields (as seen eg. in the "Taffy" pairs of galaxies). Additionally, the plumes are likely to be the tidal dwarf galaxy candidates.

Methods. We performed radio continuum mapping observations at 2.64 GHz using the 100-m Effelsberg radio telescope. We obtained total power and polarised intensity maps of the Triplet. These maps were analysed together with the archive data, and the magnetic field strength (as well as the magnetic energy density) was estimated.

Results. Extended emission was not detected either in the total power or the polarised intensity maps. We obtained upper limits of the magnetic field strength and the energy density of the magnetic field in the Triplet. We detected emission from the easternmost clump and determined the strength of its magnetic field. In addition, we measured integrated fluxes of the member galaxies at 2.64 GHz and estimated their total magnetic field strengths.

Conclusions. We found that the tidal tail hosts a tidal dwarf galaxy candidate that possesses a detectable magnetic field with a non-zero ordered component. Extended radio continuum emission, if present, is weaker than the reached confusion limit. The total magnetic field strength does not exceed 2.8 μG and the ordered component is lower than 1.6 μG.

Key words. galaxies: groups: individual: Leo Triplet – galaxies: interactions – intergalactic medium – galaxies: magnetic fields – radio continuum: galaxies – polarization

1. Introduction

Galaxy groups are known to contain large reservoirs of intergalactic gas (Trinchieri et al. 2005). The intergalactic matter is a subject to violent tidal interactions (Hickson 1982) caused by gravitational forces of the member galaxies. Studies of H I morphologies revealed that there is a variety of objects that contain outflows visible in the neutral hydrogen line (e.g. Williams et al. 1991; Yun et al. 1994; Stierwalt et al. 2009). There are two different types of intergalactic H I emission: "wells" and "streamers". Which of these is present depends on the compactness of the system. In compact groups, the gravitational forces prevent the gas from escaping from the intergalactic space between the galaxies, and the emitting medium is usually contained in a potential well between them (e.g. HCG 44, Williams et al. 1991, or the "Taffy" pairs of galaxies, Condon et al. 1993, 2002b; Drzazga et al. 2011). Conversely, loose groups are sometimes called "streamers", because the emitting gas – now weakly bound to the group members – forms bridges and tails that extend far into the intergalactic space, like in the M81/M82 group (Yun et al. 1994).

The magnetic fields can play a significant role in the evolution and dynamics of galaxy systems, because the energy densities of the thermal and magnetic components may be comparable. Not much is known about the magnetic fields in galaxy groups, however. Several studies were carried out in compact groups, especially in Stephan's Quintet. Xu et al. (2003) detected intergalactic nonthermal emission (thus an intra-group magnetic field) in that group. Our own studies (Nikiel-Wroczyński et al. in prep.) revealed intergalactic polarised emission between its member galaxies. The magnetic field energy density was determined to be approximately 5×10^{-12} erg/cm^3 – comparable to the thermal energy density estimated from X-ray observations (Trinchieri et al. 2003). Additionally, we found that the strength of the magnetic field of a tidal dwarf galaxy candidate SQ-B is comparable to that of normal spiral galaxies.

The origin of the intergalactic magnetic fields is lively debated and a variety of physical processes was proposed (e.g. reviews by Rees 2002; and Stone 2002). Usually, two scenarios are suggested: Kronberg et al. (1999) proposed dwarf irregular galaxies with strong winds that expell magnetic fields into intergalactic space (which was subsequently supported by numerical simulations by Siejkowski et al. 2010). Because these dwarfs are not always present in galaxy groups, the scenario of the production of the magnetic field in spiral galaxies and interaction-driven supply to the intergalactic space (as in the Antennae galaxies, Chyży & Beck 2004) is another possibility.

⋆ Based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg.

Table 1. Properties of the emission from the Leo Triplet sources at 2.64 GHz.

NGC	TP [mJy]	PI [mJy]	Pol. fract. [%]	Mean pol. ang. [°]	α^1	Tot. magn. field [μG]
3623	19 ± 2[2]	1.3	7	10	n/a	3.5 ± 1
3627	299 ± 14	15	5	25	0.69 ± 0.14	11 ± 1
3628	364 ± 17	18	5	98	0.59 ± 0.15	9 ± 1.5
TDGc	5.6 ± 1.0	1.0	20	35	0.7 ± 0.3	3.3 ± 0.5

Notes. [(1)] Calculated between our 2.64 GHz observations and 1.4 GHz data from Condon et al. (2002a). [(2)] Background sources not subtracted (see Sect. 4.1 for details).

However, insufficient observational data make it impossible to distinguish whether one of these mechanisms is dominating or another explanation is needed. Likewise, little is known if magnetic fields in tidal dwarf galaxy (TDG) candidates are a common phenomenon. The properties and strength of these fields are scarcely explored. Thus, deep studies of various galaxy groups, of both streamer and compact types, are needed.

The Leo Triplet, also known as Arp 317 (Arp 1966), is an example of a nearby streamer group. With its distance of 15.7 Mpc it is among the nearest objects of this type. The group consists of three tidally interacting spiral galaxies, NGC 3623, NGC 3627, and NGC 3628. The galaxies are connected by bridges of neutral gas (Stierwalt et al. 2009; Haynes et al. 1979). The most prominent one is the tidal tail that extends eastwards from NGC 3628, which is visible also in the infrared at 60 and 100 microns (Hughes et al. 1991).

Since NGC 3627 possesses a perturbed magnetic field (see Soida et al. 1999, 2001 for details), the question arises if the field is being stripped from galaxies into the intergalactic medium. As a possible explanation of the unusual morphology of NGC 3627, including its magnetic field, a collision with a dwarf galaxy was recently suggested by Weżgowiec et al. (2012). The tidal tail of the Leo Triplet is known to host several H I clumps, spatially coincident with optical traces of star formation reported by Chromey et al. (1998), indicating that they might be TDG candidates. This could lead to the conclusion that both the intergalactic and interstellar matter of spiral galaxies in the Leo Triplet galaxy group can be influenced by dwarf objects via ram-pressure/collision heating and magnetic field enhancement. Therefore, studying TDG candidates becomes an important part of the studies of galaxy groups.

The proximity of the Triplet and its angular size of nearly 1° mean that it is best observed with a single-dish telescope. Such observations are characterised by high sensitivity to extended structures. This allows searching for traces of magnetic field in H I clumps – which constitute TDG candidates because they exhibit traces of stellar formation. Therefore we performed a deep mapping of the Triplet using the 100-m Effelsberg radio telescope at 2.64 GHz. Our results are presented and discussed below.

2. Observations

We mapped the Triplet in June 2012 with the 100-m Effelsberg radio telescope. Observations were performed around the frequency of 2.64 GHz, using a single-beam receiver installed in the secondary focus of the telescope. The receiver has eight channels and total bandwidth of 80 MHz. The first channel (central frequency 2604 MHz) was dropped due to the radio frequency interference (RFI). We performed 12 coverages with a size of $80' \times 80'$ each, scanned alternatively along RA and Dec. We used a scanning velocity of 120′/min and a grid size of 2′. The data reduction was performed using the NOD2 data analysis system. The maps were averaged and combined to reduce the scanning effects using the basket-weaving method (Emerson & Gräve 1988), yielding final Stokes I, Q and U maps. During the observations we used the radio source 3C286 to establish the flux density scale. The flux of the calibrator was taken from Mantovani et al. (2009). The polarisation was calibrated using 3C286 as well. We assumed no circular polarisation (Stokes V signal = 0). The polarised fraction from our observations is equal to $11.2 \pm 0.1\%$ and the polarisation position angle is $33° \pm 4°$ – consistent with the values given in the aforementioned article. The instrumental polarisation does not exceed 1%. The Astronomical Image Processing System (AIPS) was used to produce the distribution of the polarised intensity and the polarisation angle. The resolution of the final maps is 4.′5 (half-power beam width).

The uncertainties of the integrated flux densities include a 5% uncertainty of the flux scale determination. The term "apparent polarisation B-vectors" used in this paper is defined as the observed polarisation E-vectors direction rotated by 90°, uncorrected for the Faraday rotation. Because the foreground Faraday rotation is relatively low (20°–30° based on the data presented by Taylor et al. 2009), these vectors constitute a reasonable approximation of the sky-projected magnetic field.

3. Results

Table 1 presents the properties of the detected sources that belong to the Leo Triplet. Details on the total and polarised emission can be found in Sects. 3.1 and 3.2.

3.1. Total power emission

Figure 1 shows the distribution of the total power (TP) emission superimposed with apparent B-vectors of polarised intensity, obtained at the center frequency of 2644 MHz with the 100-m Effelsberg radiotelescope. The rms noise level of the total power map is 1.0 mJy/beam. The field of view is dominated by strong background sources. However, the highest signal comes from NGC 3628. The total intensity of that galaxy is equal to 364 ± 17 mJy. Owing to the high signal level, emission in the vicinity of NGC 3628 is affected by the sidelobes of the telescope beam. Interferometric observations (Dumke & Krause 1998) showed that the angular size of the galactic halo at 4.86 GHz is around 3′. A similar scaleheight has been reported at 1.49 GHz (Reuter et al. 1991). Therefore the 2.64 GHz emission should not exceed the main lobe of the beam and is not affected by its first negative sidelobe.

The second-most luminous object is the barred spiral NGC 3627, with an integrated flux of 299 ± 14 mJy. The third member of the Triplet, NGC 3623, is also visible, but

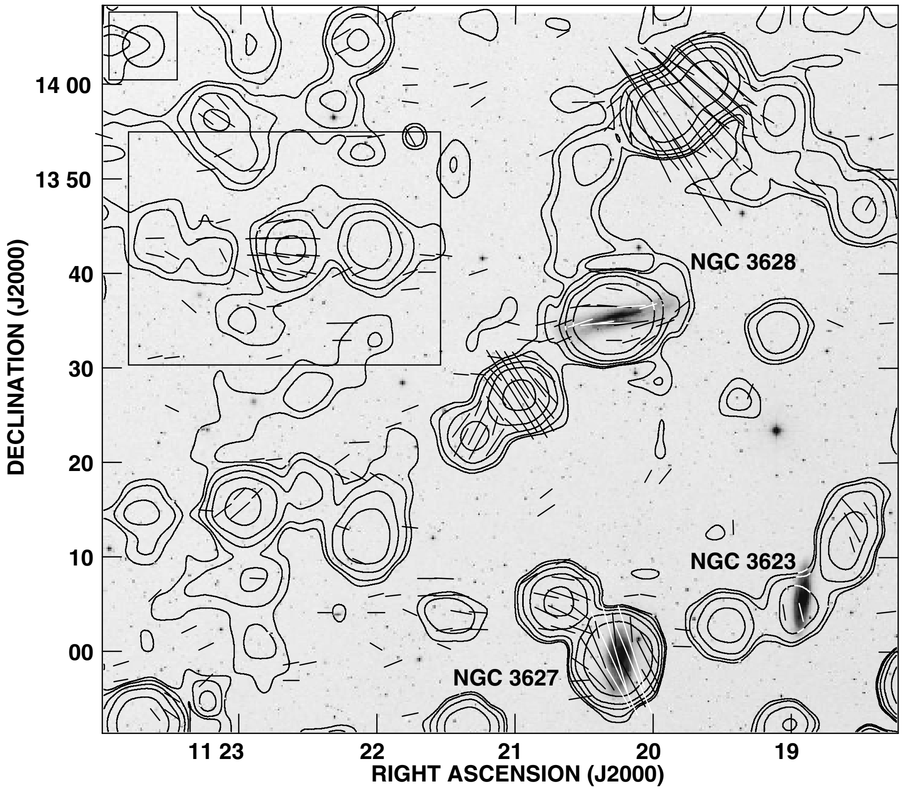

Fig. 1. Contour map of the total power emission of the Leo Triplet at 2.64 GHz. Superimposed are the apparent B-vectors of polarised intensity overlaid upon the blue image from DSS. The contour levels are 3, 5, 10, 20, 50, and 100 × 1.0 mJy/beam. A polarisation vector of 1′ corresponds to a polarised intensity of 1 mJy/beam. The beam size is 4.′5. The rectangular frame represents the area covered by Fig. 3.

is significantly weaker with an integrated flux of 19 ± 2 mJy. It should be noted here that the large beam of our observations causes flux contamination by the background sources at RA_{2000} = $11^h19^m01^s$, Dec_{2000} = +13°01′47″ and RA_{2000} = $11^h18^m57^s$, Dec_{2000} = +13°04′08″. An attempt to estimate the real value at 2.46 GHz is described in Sect. 4.1.

Most of the emission comes from (background) sources that are not associated with the Leo Triplet. There are nearly no signs of radio continuum emission from H I tails, apart from a weak source coincident with an H I clump located at RA_{2000} = $11^h23^m11^s$, Dec_{2000} = +13°42′30″ (flux of 5.6 ± 1.0 mJy; it is marked with an arrow in Figs. 2 and 3). This source could be a tidal dwarf galaxy (TDG) candidate; details can be found in Sect. 4.3.

There is a tail-like structure north of NGC 3628 (at RA_{2000} = $11^h20^m20^s$, Dec_{2000} = +13°45′00″), but a comparison with the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) shows that this probably results from smoothing of two point sources with the large beam of the telescope. Two luminous sources visible eastwards from NGC 3628 (at RA_{2000} = $11^h22^m00^s$, Dec_{2000} = +13°42′30″ and RA_{2000} = $11^h22^m40^s$, Dec_{2000} = +13°42′20″) are not connected to the H I tail either.

3.2. Polarised intensity

Figure 2 presents the distribution of the polarised intensity (PI) with apparent B-vectors of the polarisation degree. As mentioned in Sect. 2, the expected amount of the Faraday rotation is approximately 20−30°. The rms noise level is equal to 0.35 mJy/beam. Similarly to the total power emission map, the polarised intensity distribution shows mostly background (point) sources that are not related to the object of study. All three main galaxies were detected, with mean polarisation fraction for NGC 3623, NGC 3627, and NGC 3628 equal to 7%, 5%, and 5%. The only extended structure is the disk of NGC 3628. The PI vectors at 2.64 GHz are oriented along the galactic plane, resembling the structure previously reported at 4.86 GHz by Soida (2005).

There is also a marginal detection for the TDG candidate at the 2.5σ level. Its polarisation degree reaches about 20%. However, because the detection is very close to the noise level, the real polarisation degree can be significantly different from the value we derived (it is presumably lower).

4. Discussion

4.1. Integrated flux densities of the member galaxies

The radio spectrum of the member galaxies has already been investigated in several articles, allowing us to compare the flux values from our study with previous works. Table 2 presents a comparison of our data with results from de Jong (1967), Kazes et al. (1970), and Pfleiderer et al. (1980), who all studied radio-luminous galaxies at 2.64 GHz. For NGC 3627 and NGC 3628 we obtained similar values; the better quality of the data resulted in lower measurement uncertainties. For NGC 3623 the data were much more scarce than for the other galaxies. Our value of 19 ± 2 mJy is consistent with the one given by de Jong (1967); however, because of the background source contamination mentioned in Sect. 3.1, the real value is very likely lower. To estimate the real flux value, we calculated the 2.64 GHz flux of the confusing sources using 1.4 GHz data from the NVSS (Condon et al. 1998) and assumed spectral index of 0.7. The integrated flux corrected for the background sources is equal to 6 ± 3 mJy.

To derive the spectral indices for the galaxies, we used data from Condon et al. (2002a). Our results can be found in Table 1. The value of 0.69 ± 0.14 derived for NGC 3627 agrees well with the mean spectral index given by Soida et al. 1999 (0.64 ± 0.04). For NGC 3628, our measurement (0.59 ± 0.15) and the mean

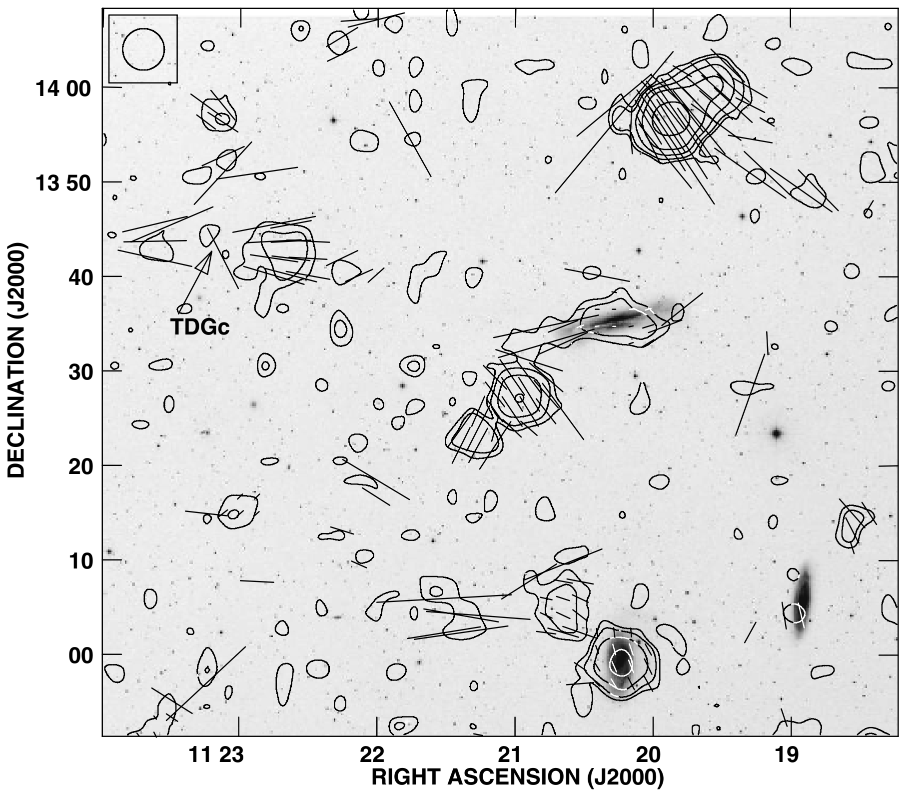

Fig. 2. Contour map of the polarised intensity of the Leo Triplet at 2.64 GHz. Superimposed are the apparent B-vectors of the polarisation degree overlaid upon the blue image from DSS. The contour levels are 3, 5, 10, 20 and 50 × 0.35 mJy/beam. A polarisation vector of 1′ corresponds to a polarisation degree of 2%. The TDG candidate is marked with an arrow. The beam size is 4.′5.

Table 2. Integrated fluxes (in mJy) for the member galaxies at 2.64 GHz.

NGC	this study	de Jong	Kazes	Pfleiderer
3623	6 ± 3[1]	≤40	no data	no data
3627	299 ± 14	359 ± 28	206 ± 41	310 ± 50
3628	364 ± 17	280 ± 22	240 ± 48	410 ± 70

Notes. References to the original publications can be found in the text. [(1)] Background sources subtracted (see Sect. 4.1 for details).

spectral index from Dumke et al. 1995 (0.67 ± 0.02) also agree well. For NGC 3623, the contamination prevents us from giving reliable estimate of its spectral index; however, using the flux value after subtracting the background sources, we obtained $\alpha = 0.75 \pm 0.2$ – which is within uncertainties consistent with the other two galaxies.

4.2. Constraints on the magnetic field strength of the Leo Triplet

To calculate the magnetic field strength, we assumed energy equipartition between the cosmic ray (CR) and the magnetic field energies and followed the procedure outlined by Beck & Krause (2005). Because large-scale magnetised outflows were not detected, only upper constraints for the magnetic field strength can be estimated. For the H I tail, we adopted cylindrical symmetry and a diameter of at least 25 kpc based on images presented by Stierwalt et al. (2009) and physical dimensions calculated from the NASA Extragalactic Database (NED). The extragalactic emission is typically characterised by a rather steep spectrum, with $\alpha > 1.0$ (e.g. Pacholczyk 1973; Chyży & Beck 2004). However, this refers to the CR electrons, not to the protons, which have higher energies than the electrons and lose their energy more slowly (Beck & Krause 2005). Moreover, higher losses of the CR electrons result in an increase of the proton-to-electron ratio K_0. On the other hand, in dense star-forming regions, interactions between CR protons and the nuclei of the IGM gas may result in the generation of the secondary electrons (e.g. Dennison 1980; Ensslin et al. 2011), for which it is yet unknown if the equipartition formula is applicable. Recent investigations by Lacki & Beck (2013) show that it is still valid for starburst galaxies, but nothing is known for the intergalactic fields. However, because the generation of secondary electrons would be a rather extreme scenario, we assumed that the K_0 value is equal to 100. The magnetic field strength is rather weakly bound to the proton-to-electron ratio; their dependence is given by a power-law function, and for the Leo Triplet, a change of the K_0 value by an order of magnitude results in adjusting the magnetic field strength by not more than a factor of two. The nonthermal spectral index was estimated to be 1.1.

To obtain the constraints, we used the rms values for the TP and PI emission as the upper limits for the nonthermal intensity. Using the parameters mentioned above, we obtained a total magnetic field strength of $\lesssim 2.8\,\mu$G, an ordered field component of $\lesssim 1.6\,\mu$G and a magnetic field energy density of $\lesssim 3.4 \times 10^{-13}$ erg/cm^3. Comparing these values with those obtained for Stephan's Quintet (Nikiel-Wroczyński et al., in prep.) and the "Taffy" galaxy pairs (Condon et al. 2002b; Drzazga et al. 2011), the large-scale magnetic field – if present – has an energy density lower by approximately two orders of magnitude than in the Quintet and the first Taffy pair, and about an order of magnitude lower than in the second Taffy pair. It is possible, however, that the magnetic field energy in the Leo Triplet is not in equipartition with the CR energy.

To make the picture more complete, we calculated the magnetic field strength also for the member galaxies. For NGC 3627 and NGC 3628 we used the spectral index values derived in

Sect. 4.1 and a pathlength of 2–4 kpc and 8–12 kpc, respectively. For NGC 3623 we decided to use our estimate of 0.75 ± 0.2 (calculated after subtracting the background sources); the pathlength was adopted as 6–8 kpc. The magnetic fields of the first two galaxies (see Table 1) are relatively strong, although similar to the median value for the galaxies in the field, 9 ± 1.3 μG (Niklas 1995). A slightly higher result obtained for NGC 3627 might be due the aforementioned collision with a dwarf galaxy (Weżgowiec et al. 2012). The magnetic field of NGC 3623 is weaker; however, this galaxy is smaller than the other two, which may explain the difference. It should be noted here that the values presented in this paragraph should be used only to visualize the magnitude of the magnetic field, not the exact value, due to the uncertainties in the parameter estimation. Especially for NGC 3623, the magnetic field strength estimate is influenced by the flux (and spectral index) estimate error due to the background sources.

4.3. Possible tidal dwarf galaxy?

As mentioned in Sect. 3.1, only one of the radio continuum sources visible in the TP map belongs to the H I tail. This source is spatially coincident with the H I clump reported by Stierwalt et al. (2009) that is also associated with faint emission in the optical domain (Chromey et al. 1998) and with the local maximum in the IRAS infrared data (Hughes et al. 1991). The coincidence of the recent (optical) and past (infrared) stellar formation and neutral gas indicates that this object is a TDG candidate. Such objects were first proposed by Zwicky (1956). Since the detection of a TDG candidate in the Antennae galaxies (Mirabel et al. 1992), such sources have frequently been reported in interacting systems (see e.g. Kaviraj et al. 2012).

We investigated available VLA Faint Images of the Radio Sky at Twenty-Centimeters (FIRST; Becker et al. 1995) and NVSS (Condon et al. 1998) data and found that the source was not detected by the FIRST survey, but there is a detection in the NVSS (which is more sensitive to extended emission than FIRST). The total flux at 1.4 GHz is equal to 8.4 ± 0.5 mJy. Figure 3 presents contours from the NVSS overlaid on the 2.64 GHz data, clearly showing the 1.4 GHz counterpart for our detection (marked with an arrow). The faint source near $\mathrm{RA}_{2000} = 11^{\mathrm{h}}23^{\mathrm{m}}40^{\mathrm{s}}$, $\mathrm{Dec}_{2000} = +13°43'30''$ is a background source.

We calculated the spectral index using our 2.64 GHz and NVSS data and obtained a value of 0.7 ± 0.3. This could indicate that the radio continuum emission is coming from a recent star-formation period, supporting our claim for a TDG candidate. The size of the TDG candidate was assumed to be 4–6 kpc, because Chromey et al. (1998) gave 5.1 kpc as the size of the stellar clump. Using the same method as in Sect. 4.2, we obtained a total magnetic field strength ≈3.3 ± 0.5 μG and a magnetic field energy density ≈4.5 ± 1.5 × 10^{-13} erg/cm^3. These values are somewhat lower than for the TDG candidate found in Stephan's Quintet (Nikiel-Wroczyński et al., in prep.), but still reasonable for a large-scale magnetic field: Niklas (1995) derived B_{TOT} = 9 ± 1.3 μG as mean for the normal-sized spiral galaxies – a value about three times higher. The clump was marginally detected in the PI map. If we attribute this detection to the TDG candidate, it gives a polarisation degree of about 20% (see Sect. 3.2) and yields a strength of the ordered magnetic field of ≈1.5 ± 0.3 μG.

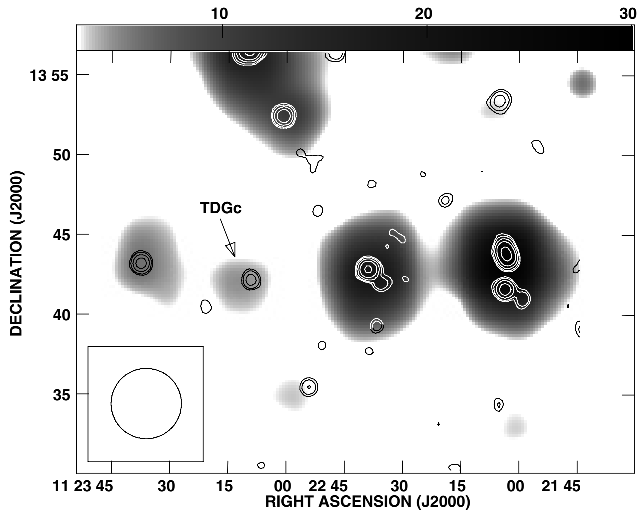

Fig. 3. Contours of the total power emission taken from the NVSS overlaid on a greyscale Effelsberg map of the TDG candidate at 2.64 GHz. The contour levels are 3, 5, 10, 20, and 50 × 0.45 mJy/beam. The TDG candidate is marked with an arrow. The beam size of the contour map is 45″. The faintest structures in the greyscale are at the 3σ level. The beam ellipse in the picture represents the 4.′5 Effelsberg beam.

5. Summary and conclusions

We observed the Leo Triplet of galaxies using the 100-m Effelsberg radio telescope at a frequency of 2.64 GHz. We obtained maps of total power (TP) emission and polarised intensity (PI). These maps were analysed together with the available archive data, yielding the following results:

- Although the high sensitivity of our observations did not allow a direct detection of the H I bridges in the radio continuum at 2.64 GHz (neither in the TP nor in the PI map), we were able to calculate upper limits for the magnetic field in the intergalactic space of the Leo Triplet. Assuming equipartition between the magnetic field and the CRs, the total field is not stronger than 2.8 μG, with an ordered component at most of 1.6 μG.
- NGC 3623, NGC 3627, and NGC 3628 are visible both in the TP and the PI map. The easternmost H I clump – visible also in the optical and infrared domains – was also detected.
- The H I clump detected in radio continuum could be an example of a tidal dwarf galaxy because there are traces of recent star formation and infrared emission in its position. The strength of its magnetic field is about 3.3 ± 0.5 μG and the magnetic field energy density reaches 4.5 ± 1.5 × 10^{-13} erg/cm^3. These values – although lower than estimated for another known TDG candidate, the SQ-B source of Stephan's Quintet – are high enough to indicate a large-scale magnetic field. The ordered component is about 1.5 ± 0.3 μG.
- The total fluxes for the main galaxies are equal to 19 ± 2 mJy for NGC 3623 (6 ± 3 mJy after subtraction of background sources), 299 ± 14 mJy for NGC 3627, and 364 ± 17 mJy for NGC 3628. The mean polarisation degree is 7, 5, and 5%, respectively.

The planned analysis of existing X-ray data for the Leo Triplet spiral galaxies will allow a comparison of the estimated intergalactic magnetic fields with the thermal properties of both galaxies and the group gaseous medium. This will provide important constraints on evolutionary models of galaxy groups.

Acknowledgements. We would like to thank an anonymous referee for helpful comments and suggestions. B.N.W. and M.S. are indebted to the whole staff of the radio telescope Effelsberg for all the help and guidance during the observations. We thank Marita Krause from the MPIfR Bonn for valuable comments. We acknowledge the usage of the HyperLeda database (http://leda.univ-lyon1.fr) and the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has made use of NASA's Astrophysics Data System. This research has been supported by the scientific grant from the National Science Centre (NCN), decision no. DEC-2011/03/B/ST9/01859 and by the Dean of the Faculty of Physics, Astronomy and Applied Computer Sciences of the Jagiellonian University, decision no. DSC/0708/2012. R.B. and D.J.B. acknowledge support by the DFG SFB 591 "Universal Behaviour of non-equilibrium plasmas" and DFG FOR 1254, "Magnetisation of Interstellar and Intergalactic Media".

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