Searching for the Magnetized Tidal Dwarf Galaxies in Hickson Compact Groups: HCG 26, 91, and 96

Blazej Nikiel-Wroczynski1,2

1 Astronomical Observatory of the Jagiellonian University, ul. Orla 171, 30-244 Kraków, Poland; blazej.nikiel_wroczynski@uj.edu.pl
2 Leiden Observatory, Leiden University, Oort Gebouw, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands

Received 2018 October 14; revised 2019 September 2; accepted 2019 September 5; published 2019 November 5

Abstract

In this work, archive 1.4 and 4.86 GHz radio continuum data from the Very Large Array were re-reduced and, together with the 1.4 GHz maps from the NRAO VLA Sky Survey, investigated for the presence of detectable, nonthermal continuum radio emission that could be associated with the tidal dwarf galaxy (TDG) candidates in HCG 26, 91, and 96. Radio emission highly coincident with the optical and Hα emission maxima of the TDG candidate HCG 91i (estimated physical separation of less than 150 pc) was revealed. Should this emission be intrinsic to this object, it would imply the presence of a magnetic field as strong as 11–16 μG—comparable to that found in the most radio-luminous, star-forming dwarf galaxies of non-tidal origin. However, the star formation rate derived for this object using the radio flux is about two orders of magnitude higher than the one estimated from the Hα data. Analysis of the auxiliary radio, ultraviolet, and infrared data suggests that either the radio emission originates in a background object with an aged synchrotron spectrum (possibly a GHz-peaked source), or the SFRHα estimate is lower due to the fact that it traces the most recent star formation, while most of the detected radio emission originated when what is known as HCG 91i was still a part of its parent galaxy. The latter scenario is supported by a very large stellar mass derived from 3.6 to 4.5 μm data, implying a high star formation rate in the past.

Unified Astronomy Thesaurus concepts: Hickson compact group (729); Galaxy tides (623); Tidal interaction (1699); Star formation (1569); Radio astronomy (1338); Extragalactic magnetic fields (507)

1. Introduction

The idea that small, self-gravitating entities can form out of the debris left by collisions and close passages of “normal” galaxies is a relatively new one, as it was proposed only about 60 yr ago (Zwicky 1956). Zwicky analyzed several aspects of the galactic interactions, e.g., the emergence of large tails, like that of the Leo Triplet, and on the basis of the disputed cases, came to a conclusion that defines the unique character of the tidal dwarf galaxies (TDGs). However, albeit novel and (as eventually revealed to be) correct, Zwicky’s idea did not gain much attention for more than 30 yr. This was mainly due to the technical limitations of the instruments used that particular day that simply could not achieve the sensitivity required to trace the weak light produced by the TDGs. In 1992, Mirabel et al. (1992) announced a detection of such an object at the tip of the tidal tail of a famous merging galaxy pair, the Antennae. With this first discovery, the era of studying TDGs began.

The following years yielded a number of case studies of TDGs, with examples of such objects detected in, e.g., Arp 245 (Brinks et al. 2004), the Virgo Cluster (Duc et al. 2007), galaxy groups like M81 (Makarova et al. 2002), or in a number of Hickson Compact Groups (HCGs; Hickson 1982), by Hunsberger & Zaritsky (1996). An important warning has also been formed: as only about 50% of the TDGs can survive for as long as the Hubble time (Bournaud 2010), and usually self-gravitation is only assumed, not proven, it is advisable to call these numerous detections “candidates” (TDGc), as they are probably, but not certainly, galaxies (Kaviraj et al. 2012). The growing database of supposed dwarfish galaxies with a tidal origin was calling for a statistical approach, in which typical parameters and traits of TDGs could be analyzed. This was done by Kaviraj et al. (2012), who used the SDSS DR6 data (Adelman-McCarthy et al. 2007) and built a sample of more than 3000 nearby (not further than z = 0.1) galaxy mergers that could possibly host TDG candidates. Inside these systems, as many as 405 candidate objects have been identified.

Studies on TDGs in galaxy groups constitute a separate and growing chapter in the history of their observations. The TDG formation efficiency drops down rapidly with increasing density of the host systems (Kaviraj et al. 2012). They are much more scarce in galaxy groups than in pairs, and probably are eager to evolve differently. Complicated dynamics of the multi-galaxy systems increases the possibility that a newly born TDG candidate/progenitor will be absorbed in the subsequent galactic collisions (e.g., in the case of the Leo Triplet; Woźniec et al. 2012). Despite this impediment, studies carried out on the HCGs show that these systems can be quite abundant with TDG candidates. In particular, HCG 92—the famous Stephan’s Quintet (Stéphan 1877) has been concluded to host at least 20 candidate objects (Hunsberger & Zaritsky 1996), two of them (denoted SQ–A and SQ–B; Xu et al. 2003) being visible in multiple spectral regimes. A recent study by Eigenthaler et al. (2015) shows that other HCGs are also accompanied by TDG candidates, and some of these groups can host a significant number of them (e.g., HCG 91).

When discussing the TDG candidates found in galaxy groups, two of them in particular should be mentioned: SQ–A, and SQ–B, which are located in the tidal tail of NGC 7319, a member galaxy of the Stephan’s Quintet. What is special about these objects is that they emit in the radio continuum (Xu et al. 2003). This emission has a nonthermal character, and there are hints that it is partially polarized in the case of the latter one (Nikiel-Wroczynski et al. 2013a), signifying the existence of a detectable magnetic field, probably at least ordered (if not genuinely regular), inside this objects. Although it is a
possibility that the matter forming a TDG is magnetized, it is certainly not an exotic one—most of the spiral galaxies host relatively strong magnetic fields (Niklas 1995), and these are mostly spirals that serve as progenitors to TDG candidates (TDGs; Kaviraj et al. 2012)—SQ–A and SQ–B remain the single known examples of the magnetized TDGc so far. Hints for the radio emission from a TDGc in Leo Triplet (Nikiel-Wroczyński et al. 2013) have turned out to be caused by a background source smeared by the large beam of the single-dish observations used in that study (Nikiel-Wroczyński et al. 2014). Attempts to detect radio emission in other TDGc—e.g., in the Antennae, K. Chyży, (2019, private communication)—have turned out to be fruitless so far.

In general, detection of the magnetic field inside, or around a TDGc should not be very surprising. Conditions favorable for their formation, like the presence of spiral galaxies, or effective processes of star-forming, are preferable for the magnetic fields to be amplified, too. However, magnetic fields found in dwarf galaxies are usually weaker than those found in spiral galaxies: whereas the median strength of the magnetic field in spiral galaxies is $9 \pm 1.3 \, \mu G$ (Niklas 1995), values as low as a few microgauss are usually reported for the dwarf ones (see Chyży et al. 2011 and references therein). Strong magnetic fields are found only in the so-called starburst dwarf galaxies (e.g., NGC 1569, Kepley et al. 2010, or NGC 4449, Chyży et al. 2000) and can be considered an exception to this rule. Alas, the sample of the studied TDG candidates is still too scarce to investigate the role and general properties of the magnetic fields inside them, and it is desirable to enlarge the sample.

In this paper, the results of investigating the radio maps of those HCGs that have been marked by Eigenthaler et al. (2015) as possible hosts of TDG candidates are presented. Archive radio data from the Very Large Array (VLA) and the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) were analyzed for each of these systems, revealing radio emission possibly associated with HCG 91i both at 1.4 and 4.86 GHz. The paper is organized as follows: Section 2 contains the basic information on the data used, as well as information about their processing. Section 3 describes the radio maps of the studied groups and relates them to the list of TDG candidates compiled by Eigenthaler et al. (2015). Section 4 discusses the arguments in favor of and against possible connection between the detected radio emission and HCG 91i, as well as evaluates different explanations for the detected signal. Section 5 summarizes the findings of this article.

### Table 1

| HCG No. | L-band Project | TOS (s) | Resolution | Noise (μJy/beam) | Conf. | C-band Project | TOS (s) | Resolution | Noise (μJy/beam) | Conf. |
|---------|----------------|---------|------------|------------------|-------|----------------|---------|------------|------------------|-------|
| 26      | AM344          | 930     | $879 \times 5\,\text{″}$ | 70 | A/B | AM219 | 340 | $178 \times 1\,\text{″}$ | 30 | C |
| 91      | AT149C         | 440     | $1278 \times 8\,\text{″}$ | 250 | B/C | AC345B | 190 | $873 \times 3\,\text{″}$ | 125 | C |
| 96      | AS267          | 1350    | $574 \times 4\,\text{″}$ | 120 | B | AM219 | 350 | $172 \times 0\,\text{″}$ | 75 | A |

For each of the three systems studied, maps of the radio emission at 1.4 and 4.86 GHz were made. They are included in Figure 1 (HCG 26), Figure 3 (HCG 91), and Figure 5 (HCG 96). Each of them is a three-image panel, with the upper part presenting the NVSS data, the middle—1.4 GHz high-resolution archive data, and the bottom one—high-resolution archive data taken at 4.86 GHz. Area covered by the each of the radio maps was chosen in such a way that all of the TDG candidates are included. Throughout the paper, spatial distances were calculated according to Hickson et al. (1992).

First of the objects, HCG 26, is well visible in the NVSS, with an extension of the radio contour that encompasses all three TDG candidates (Figure 1, upper panel). The 1.4 GHz archive data (Figure 1, middle panel) show that most of this emission is likely to originate within the central galaxy, with only an isolated patch—barely exceeding the 3 rms level—located close to the TDG candidates. However, a close inspection (Figure 2) reveals that the maximum of the radio emission at 1.4 GHz (0.34 ± 0.07 mJy) is displaced from the optical structure; the distance between the aforementioned patch and the closest candidate (HCG 26b) is comparable to the size of the telescope beam. At 4.86 GHz (Figure 1, lower panel), none of the aforementioned structures is still visible. Therefore, it is concluded that the detected emission is not associated with any of the TDG candidates.

Data sets for the second group, HCG 91, are noticeably shorter in time (see Table 1); this is reflected in the highest noise level among all data sets at both L- (225 μJy/beam) and C-band (125 μJy/beam). HCG 91 has also the highest number of possible subsecond resolution are used). As many of them form close to their host galaxies (Kaviraj et al. 2012), they are prone to be mistaken with other similar, but not self-gravitating entities, e.g., $H_\text{II}$ regions. Therefore, in order to prevent beam smearing of the emission from several entities into one, only loose-configuration, archive VLA data (at most B-configuration at 1.4 GHz, and C-configuration at 4.86 GHz) were chosen.
TDGs among those investigated in this study—10. Out of this number, four are possible radio emitters: HCG 91c and HCG 91d are immersed in the same radio structure as their parent galaxies, while HCG 91i and HCG 91j share a common radio contour that does not connect to their mother galaxy (Figure 3, upper panel). The higher-resolution 1.4 GHz data (Figure 3, middle panel) show that only HCG 91i seems to be a (point-source) radio emitter, with a flux density of $2.21 \pm 0.23$ mJy/beam. This source is still visible at 4.86 GHz (Figure 3), where its flux density is equal to $0.72 \pm 0.13$ mJy/beam. Closer inspection (Figure 4) reveals that both at 1.4, and 4.86 GHz, the radio contours perfectly match with the position of HCG 91i reported by Eigenthaler et al. (2015), suggesting that it is, indeed, a radio-emitting TDG candidate.

In the case of the last object in this study, HCG 96, the data sets are both the longest and have the highest resolution among the ones used in this study. The radio contours from the NVSS (Figure 5, upper panel) encompass also the candidate HCG 91a, while HCG 91b is not enclosed. Archive data at both 1.4 (Figure 5, middle panel) and 4.86 GHz (Figure 5, lower panel) show no emission outside of the parent galaxies.

4. Discussion

As most of the relations regarding star formation used in the literature data relevant for this work have been calculated under the assumption of a Salpeter Initial Mass Function (IMF; Salpeter 1955), this IMF was adopted for all of the measurements presented in this paper. In particular, the equations provided by Murphy et al. (2011), which use the Kroupa IMF (Kroupa 2001), where recalibrated by introducing a factor of 1.6, as outlined by Calzetti et al. (2007). Common values for the distances to the sources relevant for this study were also adopted, and all values dependant on them were recalculated.
4.1. What is the Origin of the Radio Emission?

Analysis of the archive data suggests that among the TDG candidates from HCG 26, HCG 91, and HCG 96, only HCG 91i is visible at 1.4 and 4.86 GHz. In order to extract the exact coordinates of the radio source, the AIPS task IMFIT was used. The derived positions, as well as the position of the $H\alpha$ emitter associated with HCG 91i given by Eigenthaler et al. (2015) are presented in Table 2. It turns out that the offset between the fitted maxima of radio emission at 1.4 and 4.86 GHz is equal to 1\textdegree2. The theoretical precision (returned by the IMFIT task) is...
around $0^\circ 6$, so this displacement is not worrying. Moreover, as the beam size at each of the frequencies is larger, it is in fact negligible. The exact distance between the detection at 4.86 GHz (where the resolution is higher) and the position estimated from H$_{\alpha}$ data is even lower—$0^\circ 3$. Assuming that the whole system is located approximately 101 Mpc away (Hickson et al. 1992), this translates into a physical separation of less than 150 pc. HCG 91j, the other nearby TDG candidate, is located as far as $11^\circ 3$—a distance larger than the size of the beam at 4.86 GHz. This altogether suggests that if the radio emission is intrinsic to any of the TDG candidates, then HCG 91i would be its most probable host.

While HCG 91i is the single detected radio source among all of the TDG candidates studied, it is not the most luminous one in the H$_{\alpha}$ line (Eigenthaler et al. 2015). HCG 91c, HCG 91d, HCG 91e, and HCG 91j have all higher H$_{\alpha}$ luminosity, while HCG 91a and HCG 91g are similar to the detected TDGc in this regard. As the H$_{\alpha}$ star formation rate (SFR$_{H_{\alpha}}$) is proportional to the H$_{\alpha}$ luminosity (Murphy et al. 2011), the most luminous object should also be the most actively star-forming one. Moreover, the 1.4 GHz emission can also be used as an estimator of the SFR (Condon et al. 2002; Murphy et al. 2011; Heesen et al. 2014), so it is possible both to estimate the expected 1.4 GHz luminosity, and the 1.4 GHz-derived SFR (SFR$_{1.4 \text{ GHz}}$)—and compare these values to each other. In order to calculate SFR$_{1.4 \text{ GHz}}$, and to estimate the expected radio flux at that frequency, Equation (17) from Murphy et al. (2011), recalibrated to the Salpeter IMF (Salpeter 1955), connecting the radio luminosity and star formation rate was used:

$$\left( \frac{\text{SFR}_{1.4 \text{ GHz}}}{M_\odot \text{ yr}^{-1}} \right) = 1.02 \times 10^{-28} \left( \frac{L_{1.4 \text{ GHz}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right). \quad (1)$$

Substituting $L_{1.4 \text{ GHz}} = 4\pi d^2 S_{1.4 \text{ GHz}}$, where $d$ is the distance to the source, and expressing $S_{1.4 \text{ GHz}}$ in (Jy), and $d$ in (Mpc), this equation takes the following form:

$$\left( \frac{\text{SFR}_{1.4 \text{ GHz}}}{M_\odot \text{ yr}^{-1}} \right) = 1.22 \times 10^{-11} \left( \frac{S_{1.4 \text{ GHz}} \cdot d^2}{\text{Jy Mpc}^{-1}} \right). \quad (2)$$

To estimate the radio flux from SFR$_{H_{\alpha}}$, this can be transformed into

$$\left( \frac{S_{1.4 \text{ GHz}}}{\text{Jy}} \right) = 13.08 \left( \frac{\text{SFR}_{H_{\alpha}} \cdot d^{-2}}{M_\odot \text{ yr}^{-1} \text{ Mpc}^{-2}} \right) \quad (3)$$

Equations (2) and (3) were then used to calculate the expected SFR/upper constraints from the radio flux/3 rms noise level, and vice versa. Apart from the detected HCG 91i, the most H$_{\alpha}$-luminous TDG candidates in each of the systems were used. The results can be seen in Table 3. It turns out that none of the TDG candidates should be detected at 1.4 GHz!

### Table 2

| Data          | $\alpha$ (J2000.0) | $\delta$ (J2000.0) |
|---------------|---------------------|---------------------|
| H$_{\alpha}$  | 22°09'06''98        | -27°46'42''44       |
| 1.4 GHz       | 22°09'06''95        | -27°46'43''00       |
| 4.8 GHz       | 22°09'07''00        | -27°46'42''22       |

**Note.** From Eigenthaler et al. (2015).
The radio flux extrapolated from the Hα data for most of these objects should not exceed a few μJy in most of the cases and are thus undetectable using the currently available radio data. The radio upper limits for the SFR of the non-detected TDGs are approximately two orders of magnitude higher than that from Eigenbenthler et al. (2015). The same conclusion is derived when using Equation (21) from Condon (1992); assuming a spectral index of 0.8, none of the TDG candidates has an expected radio flux higher than approximately 50 μJy. Such a discrepancy raises doubts if the radio emission is indeed connected to the TDG candidate; another, straightforward explanation might be that it originates in a background radio source, which is just by chance so angularly close to the Hα maximum associated with HCG 91i. Therefore, a series of different tests have been carried out, all of which are presented later in this paper. To avoid excessive usage of terms like “radio emission,” “radio source,” etc., the designation HCG 91RS will be used herein to name the radio counterpart.

4.2. Radio Spectrum of HCG 91RS

The possibility that HCG 91RS is just an imaging artefact would be one of the most straightforward explanations. However, the detection was made at two separate observing bands; moreover, at the L-band, observations were carried out using two different configurations of the VLA. As a result, the point-spread functions of each of the data sets are different, so emergence of an artefact at the same sky position is unlikely. The flux densities of HCG 91RS derived both from the NVSS and the high-resolution data are also coherent. Therefore, this scenario does not seem to be a probable one.

Additional information on the nature of a radio source can be derived from its radio spectrum. Unfortunately, HCG 91RS is not an easy target for such a study; it has a relatively steep spectrum, which hinders efforts to detect it at higher frequencies (especially as it is a rather weak emitter). In addition, in order to avoid smearing its signal with the emission from the central galaxy of HCG 91, high-resolution observations are desirable. The NRAO Data Archive lists one possibly useful data set—recorded at 8.46 GHz. Assuming the same spectral index as between L- and C-bands—0.91 ± 0.21 (α ∝ ν−α)—HCG 91RS should have a flux density of 0.45 ± 0.13 mJy at 8.46 GHz—detectable at at least the 5 rms level. However, this is not the case; either HCG 91i is extended at the angular scales larger than that of the beam (which is 0′′5 in this case) and the resolved parts are too weak to be detected, or its spectrum steepens even further between 4.86 and 8.46 GHz—the flattest slope to imply a lack of detection at the given 3 rms level is 1.41.

HCG 91i can be looked upon at the lower frequencies, too—in the TGSS ADR (Intema et al. 2016) survey; this data were collected at 150 MHz, have an angular resolution of 25″ on 25″ × sec(−19°), but come with a limited sensitivity to extended structures. Assuming a 1420 MHz flux density of HCG 91RS of 2.24 ± 0.23 mJy, and once again, α = 0.91 ± 0.21, one can expect the 150 MHz flux density to be around 20 mJy; this is, at a 13 × rms level. However, similarly to the 8.46 GHz data, this is not the case. The TGSS ADR map (see Figure 6) reveals emission from the central pair of galaxies only. If the 3 × rms level is substituted to calculate the spectral index between 150 MHz and 1.4 GHz, then the resulting value is equal to 0.31 ± 0.06. This would indicate a very flat spectrum, reaching the flatness limit for the nonthermal radio spectra (Weiler & Sramek 1988). As a result, either the radio spectrum steepens significantly in the supra-GHz regime, but is relatively flat at lower frequencies, or the low-frequency flux density is underestimated.

Gathering the radio information altogether, there are two likely explanations for the spectrum of HCG 91RS. If it is a background radio galaxy, it is a somewhat older object, with a spectrum quickly steepening around 1 GHz, or an example of a Gigahertz-Peaked Source O’Dea et al. (1991). If the emission indeed comes from HCG 91i, then the possible mechanism responsible for the low-frequency flattening could be the absorption of the synchrotron radiation on the thermal electrons in the source itself—a process that is expected to take place in star-forming regions. With TDG candidates being in fact detached, self-gravitating regions of excessive star formation—especially given the estimated SFR1.4 GHz for HCG 91RS—could explain the lack of detection at 150 MHz. A similar situation happens for the TDG candidate SQ–B from HCG 92: assuming the flux density and spectral index provided by Nikiel-Wroczyński et al. (2013a), one could expect it to be detectable in the TGSS, which is not the case. Spectrum flattening is present in star-forming regions inside galaxies. The TDGs are actually star-forming regions outside galaxies, which we expect to be self-gravitating. Thus, any effect detected in the case of the former should also be present in the latter (but not vice versa). At the higher frequency, the lack of the

| Object | Sα1.4 GHz | Sα8.46 GHz | log(SFR1.4 GHz) | log(SFR8.46 GHz) |
|--------|-----------|-----------|----------------|-----------------|
| HCG 91i | 2210      | 7.3       | 0.41           | −2.27           |
| HCG 91d | <675      | 15.7      | <−0.08        | −1.94           |
| HCG 26a | <150      | 2.8       | <−0.47        | 2.45            |
| HCG 96a | <360      | 1.5       | <−0.08        | −2.77           |

Note: The table lists the radio flux densities (in mJy) and logarithmic SFR values for three TDG candidates in HCG 91.
detection of HCG 91i can be attributed to over-resolving of the source’s structure: the 0.′5 resolution of the set translates into a physical scale of around 250 pc—smaller than the typical size of a TDG candidate.

4.3. Dust Attenuation

Given the fact that in case of HCG 91i and 91RS, it is the SFR$_{H\alpha}$ that is much lower than SFR$_{1.4 \text{ GHz}}$, a possible explanation for the mismatch between these two indicators could be the extinction of H$_\alpha$ flux on dust grains. This effect can be significant and usually can be corrected for by using either the 22, 24, or the 25 $\mu$m data (see, e.g., Calzetti et al. 2007; Murphy et al. 2011; Kennicutt & Evans 2012). It would be even more plausible reason given the fact that HCG 91i is located at the tip of a tidal arm/tail—such TDGs are prone to accumulate larger amounts of matter, including dust (Bournaud et al. 2004). There is no direct detection of 22 $\mu$m emission from HCG 91i in the WISE data, but some upper constraints can still be derived. Assuming an upper flux constraint of $\approx$2.3 mJy calculated from the catalog data on the magnitudes of the sources of interest following the instructions provided in the Explanatory Supplement to the WISE Preliminary Data Release Products and using Equations (6) and (7) from Murphy et al. (2011) (re-calibrated into the Salpeter IMF), one arrives at SFR$_{H\alpha,\text{corr}} = 0.1 M_\odot$ yr$^{-1}$. This value is more than an order of magnitude higher than the non-corrected SFR$_{H\alpha}$ from Eigenthaler et al. (2015); however, this is the theoretical maximal expected flux, and yet it is still about an order of magnitude lower, than SFR$_{1.4 \text{ GHz}}$. Therefore, dust extinction of H$_\alpha$ flux solely cannot explain the observed discrepancy.

4.4. Typical Discrepancies Between SFR$_{1.4 \text{ GHz}}$ and SFR$_{H\alpha}$ for Starburst Dwarf Galaxies

The most challenging issue in linking HCG 91i to HCG 91RS is the discrepancy between its SFR$_{1.4 \text{ GHz}}$ and SFR$_{H\alpha}$. To investigate if such a situation can be regarded as a typical one, I have used Equation (2) for a subset of nearby starbursting dwarf galaxies from McQuinn et al. (2010) for which the 1.4 GHz NVSS data (Condon et al. 1998) were available. To supplement this sample, two TDG candidates SQ–A and SQ–B were added. Distances were taken from the NASA Extragalactic Database (except for SQ–A and SQ–B, where Hickson et al. 1992 estimates were used). All of these objects are small galaxies, most of them have a diameter lower than 3 kpc (larger sizes of TDG candidates might arise from a less precise measurement). Results can be seen in Table 4. It turns out that in general, those starbursting dwarf galaxies that have significant 1.4 GHz flux have SFR$_{1.4 \text{ GHz}}$ in agreement with SFR$_{H\alpha}$. Several objects have their radio estimates about an order of magnitude lower, than that from H$_\alpha$; however, these are all relatively weak objects (in both regimes). In addition, NGC 625 and NGC 2366 are the smallest ones considered in this sample. As a result, uncertainties in radio flux can easily lead to a large mismatch between calculated SFRs.

In the case of SQ–A and SQ–B, the radio data have much higher resolution and sensitivity—hence, it should be possible to avoid such uncertainties. However, while for SQ–B, both SFR estimates are in nearly perfect agreement, which does not happen in the case of SQ–A. Here, the SFR$_{H\alpha}$ is very high—

| Object   | SFR$_{1.4 \text{ GHz}}$ | SFR$_{H\alpha}$ |
|----------|--------------------------|-----------------|
| HCG 91i/RS | 98 | 3.15 | 2.2 | <0.1 | 2.56 |
| IC 4662   | 4.4 | 1.37 | 40  | 0.08 | 0.09 |
| NGC 625   | 2.8 | 0.87 | 10  | 0.04 | 0.01 |
| NGC 784   | 5.0 | 1.55 | 3   | 0.12 | 0.01 |
| NGC 1569  | 3.4 | 1.06 | 362 | 0.24 | 0.51 |
| NGC 2366  | 1.5 | 0.47 | 20  | 0.16 | 0.01 |
| NGC 4214  | 7.5 | 2.34 | 38  | 0.13 | 0.26 |
| NGC 4449  | 5.8 | 1.81 | 270 | 0.97 | 1.11 |
| NGC 5253  | 9.3 | 2.90 | 86  | 0.40 | 0.91 |
| SQ–A$^c$  | 90 | 3.59 | 0.8  | 1.84 | 0.79 |
| SQ–B$^d$  | 90 | 3.32 | 0.6  | 0.57 | 0.59 |

Notes.

$^a$ Diameter derived from log d25 parameter from Makarov et al. (2014) (if not stated otherwise).
$^b$ Radio flux taken from this work, SFR$_{H\alpha}$ taken from Eigenthaler et al. (2015), recalculated using consistent distance estimate, and corrected for the maximal dust contamination, optical diameter roughly estimated using the background DSS map.
$^c$ Radio flux taken from Xu et al. (2003), SFR$_{H\alpha}$ taken from Xu et al. (2003) and recalculated using consistent distance estimate, optical diameter roughly estimated using the WISE Band 1 data.
$^d$ Radio flux taken from Xu et al. (2003), SFR$_{H\alpha}$ taken from Lisenfeld et al. (2016) and recalculated using consistent distance estimate, and re-calibrated from Kroupa to Salpeter IMF, optical diameter roughly estimated using the WISE Band 1 data.

Notes.

4.5. Stellar Content and SFR–M$_*$

Not only is there a large discrepancy between SFR$_{1.4 \text{ GHz}}$ and SFR$_{H\alpha}$, but also the very value of radio SFR seems to be unrealistically high: objects listed by Lisenfeld et al. (2016) exhibit star formation rates of 0.005–0.32 M$_\odot$ yr$^{-1}$, so at least an order of magnitude lower than SFR$_{1.4 \text{ GHz}} = 2.6 M_\odot$ yr$^{-1}$ for HCG 91RS. However, there are at least two known examples of TDG candidates with a relatively high SFR, namely SQ–A and SQ–B regions present in HCG 92. In order to use a consistent distance estimate for all of the derivations carried out in this study, I have recalculated the SFR$_{H\alpha}$ provided by Xu et al. (2003) for SQ–A and Lisenfeld et al. (2016) for SQ–B, arriving at 1.84 and 0.57 M$_\odot$ yr$^{-1}$, respectively. It is then feasible to test if such values would be reliable, e.g., by comparing the derived SFR to the stellar content of these objects. In order to do so, I have used the WISE 3.6 and 4.5 $\mu$m data for all three objects and calculated the stellar content using the following relation from Eskew et al. (2012). The infrared fluxes were calculated using the same instructions as in

http://wise2.ipac.caltech.edu/docs/release/prelim/expsup/wise_prelreltoc.html
Section 4.3:

\[
\left( \frac{M_*}{M_\odot} \right) = 10^{0.65} \left( \frac{(F_{3.6 \mu m})^{2.85}}{Jy} \right) \left( \frac{(F_{4.5 \mu m})^{-1.85}}{Jy} \right) \left( \frac{20 \times D}{Mpc} \right)^2.
\]

This yields stellar masses equal to \(10^{9.04} M_\odot\) for HCG 91i, \(10^{9.37} M_\odot\) for SQ–A, and \(10^{8.58} M_\odot\) for SQ–B. This in turn identifies SQ–A and HCG 91i as relatively massive TDG candidates, as the statistical study of Kaviraj et al. (2012) shows that an average stellar mass of such an object varies between \(10^{8.5}\) and \(10^{8.4} M_\odot\), depending on its location (at the base/along / at the tip of the tidal tail). These values were then substituted to the SFR–mass relation for late type galaxies given by Calvi et al. (2018). The range of expected SFR (in \(M_\odot \, yr^{-1}\)) is 0.2–1.3 for HCG 91i, 0.3–1.6 for SQ–A, and 0.1–0.6 for SQ–B. In case of SQ–A and SQ–B, it is in a good agreement with both SFR_{1.4 GHz} and SFR_{\sf H}\_; the SFR_{\sf H}\_ estimate for the former one is a bit larger than the expected value. Contrary to that, for HCG 91i, only one SFR indicator can be assumed to be similar to the predictions based on the the stellar mass—the radio one, albeit the derived SFR is nearly twice as much as the expected one. On the other hand, SFR_{\sf H}\_ for HCG 91i, even after correcting for the dust contamination, is more than an order of magnitude lower, than what one would expect from the SFR–\(M_*\) relation. As a result, not only is the star formation rate being as high as the estimated SFR_{1.4 GHz} feasible, but it turns out to be the one that best fits the SFR–\(M_*\) relation.

4.6. Variations in the SFR Over Time

Another explanation of the discrepancy between SFR_{1.4 GHz} and SFR_{\sf H}\_ could be a series of star formation bursts inside HCG 91i. SFR estimators are sensitive to stars of different age: as outlined by Kennicutt & Evans (2012), for the \(H_*\) estimator the mean age of the stars that contribute to the emission is around 3 Myr, and 90% of emission comes from the ones that are younger than 10 Myr. Other estimators are sensitive to different populations: for example, the ultraviolet tracer is sensitive to the population which has a mean age of 10 Myr, and the age range of the objects that contribute to this emission is much larger than that in the case of \(H_*\): it is 100 Myr for the far- and 200 Myr for the near-ultraviolet light. In case of the 1.4 GHz emission, the mean age is equal to 100 Myr—and the “boundary” age is not estimated. A series of subsequent bursts could result in an enhanced magnetic field/radio emission, suggesting a still high SFR, while the most current value, traced by the \(H_*\) emission would be lower if the object under consideration is in a more quiescent phase. If this is indeed the case of HCG 91i, then it should still be a strong UV emitter. In order to evaluate this scenario, I have checked the GALEX FUV and NUV maps. The results are not encouraging: first of all, there is no UV source that could be directly associated with HCG 91i. The closest ones are very faint (NUV fluxes of less than \(15 \, \mu Jy\)), and only one of them was detected in both FUV and NUV. The distance between them and the radio maximum is significant—more than 10', so at least 4.5 kpc—more than the expected size of the whole TDG candidate. I have estimated the SFR using the relations presented by Kennicutt & Evans (2012), derived from the earlier works on Hao et al. (2011) and Murphy et al. (2011), and recalibrated for the Salpeter IMF. The FUV and NUV fluxes were taken for the nearest source detected in both of these bands and corrected for the dust extinction using the WISE Band 4 upper flux limit of 2.3 mJy. The dust-enshrouded SFR$_{\sf UV}$ is equal to approximately 0.03 \(M_\odot \, yr^{-1}\), and SFR$_{\sf NUV}$ is approximately 0.04 \(M_\odot \, yr^{-1}\). These values are lower than those estimated for the dust-enshrouded SFR_{\sf H}\_ (and thus, much lower than the SFR_{1.4 GHz}). Therefore, the hypothesis of subsequent burst can be safely discarded.

4.7. An Inherited Magnetic Field?

One of the most fundamental differences between the SFR_{\sf 1.4 GHz} and SFR_{\sf H}\_ estimators is the evolutionary stage of the objects they probe. The latter one relies on the presence of an ionized gas surrounding a young, massive star. Contrary to that, the radio one is aimed at a much older ones: it is, in fact, a post mortem survey, as the synchrotron emission relies on the relativistic electrons supplied by the supernovae. Traces of these processes fade away on different timescales: radio emission can still be detectable tens of Myr after the last electrons where supplied. Therefore, one can propose a hypothesis that while both the radio and \(H_*\) emission are connected to HCG 91i, only the latter is caused by processes intrinsic to (or triggered inside) this object. The majority of the radio emission is caused by an electron population supplied to the magnetic field when what is now regarded as a TDG candidate was still a part of its parent object. Analysis of the radio spectrum of HCG 91RS seems to be consistent with this scenario. With a spectral index of 0.91 ± 0.21, it is a rather steep (thus aged) one. Young supernovae remnants have in general much flatter indices: the lower limit is assumed to be equal to 0.3 (Weiler & Sramek 1988). Such flat spectra are indeed seen in case of disk star-forming regions—it happens in the case of the dwarf starburst galaxy pair Arp 269 (Nikiel-Wroczyński et al. 2016). A rough estimate of the spectral age, made under the assumption that the break frequency of the spectrum is already below 4.86 GHz, suggests that the radio emission must be older than approximately 10–15 Myr—likely more. In addition, the aforementioned scenario easily explains the excessive strength of the magnetic field associated with HCG 91RS (see Section 4.8). The obtained value of 11–16 \(\mu G\) is, as already mentioned, similar to that of example disk star-forming regions. If HCG 91i began its life as a region of vigorous star formation inside the spiral arm of HCG 91A and was later separated due to the action of tidal forces, then a strong, “remnant” magnetic field would be indeed expected. While at first glance the scenario where HCG 91i and HCG 91RS are the same object but their emission represents fundamentally different moments in its past seems to be able to easily explain the observed discrepancies, it also has several important caveats. There is neither information on the interaction history of the whole group nor about the stellar population of HCG 91i. It is then impossible to address the problem quantitatively, e.g., compare the spectral age with the expected time elapsed since the interaction started. Additional studies on HCG 91i and the history of the system as a whole are necessary to test the feasibility of this hypothesis.

An additional hint for the feasibility of the hypothesis described above comes from the analysis of optical maps: albeit there are four more \(H_*\)-luminous TDG candidates in their host system than HCG 91i, it is the only one luminous enough to be included in the USNO A-2.0 catalog with an absolute magnitude in these filters of \(\approx -16\), and the only one to be
unambiguously detected in the infrared 3.6 and 4.5 μm data. Even in the background maps used for the radio images, it is the single TDG candidate with a clear optical counterpart. However, again, there is a possibility that the observed object is just a superposition of a TDG candidate and a distant background source.

Alas, the identification of HCG 91RS with HCG 91i remains ambiguous. Whereas there is neither a certain explanation for the discrepancy between SFR1.4 GHz and SFRH, nor the possibility of a background active galactic nucleus (AGN) galaxy can be ruled out fully, analysis of the stellar content and its relationship with the system’s expected SFR clearly suggests that values similar to SFR1.4 GHz would be expected. Additional data would be needed to prove, or disprove the hypothesis that HCG 91i is indeed another example of a rare, starbursting TDG candidate possessing a detectable magnetic field.

Last but not least, it is also worth mentioning that many of the arguments presented in this study could be better assessed if there was considerable literature data on radio-emitting TDG candidates. With only three of such objects known (assuming that HCG91 i is one of these), it is impossible to evaluate if any studied parameter can be considered typical (or not) for this class. A larger study aimed at revealing new radio-emitting TDG candidates is thus desirable.

4.8. Magnetic Field Inside the TDG Candidates

If HCG 91RS is indeed the radio counterpart of HCG 91i, then it is possible to use the flux densities at 1.4 and 4.86 GHz to estimate the strength of its magnetic field. The spectral index of $0.91 \pm 0.21$ was substituted into the BFELD code (Beck & Krause 2005) that calculates the basic properties of the magnetic field, together with a pathlength of 2000–4000 pc (similar to the size of the optical counterpart), and the proton-to-electron ratio of 100, which is believed to be maintained even in the starburst galaxies (Lacki & Beck 2013). The estimated magnetic field strength (under the assumption of equipartition of energy between the magnetic field and the cosmic rays) is then $11–16 \mu G$. This is a strong magnetic field—stronger than the typical ones found for spiral galaxies by Niklas (1995) and approximately two times stronger than the one derived for the radio-emitting TDGs SQ–A and SQ-B (Nikiel-Wrocyński et al. 2013a). Such a strength is similar to that of the compact disk areas of star formation. Beck & Wielebinski (2013) list several objects that host even stronger magnetic fields, and the study of the magnetic field of starburst dwarf spiral galaxy NGC 4490 (Nikiel-Wrocyński et al. 2016) reveals a handful of disk starburst regions hosting magnetic fields exceeding $20 \mu G$ in strength. Compared to the other dwarf galaxies, HCG 91i seems to possess a magnetic field similar to that of the starburst dwarf galaxies studied by Chyży et al. (2011).

While no detection was made in case of any other TDG candidate from the list of Eigenthaler et al. (2015), it is possible to estimate the upper constraints for the strength of magnetic field in these entities. Using the same pathlength as before, and calculating the spectral index using with the 3 rms levels of the respective radio data, it turns out that the magnetic fields of $6–8 \mu G$ strength can still remain undetected, due to high rms noise levels. Such a value would also apply to HCG 91i, if the radio emission comes from a background source. A more sensitive study would allow one to derive more strict constraints.

5. Conclusions

This work attempted to detect the radio counterparts of the TDG candidates in compact galaxy groups HCG 26, 91, and 96. On the basis of the gathered and analyzed material, the conclusions are as follows:

1. There are clear signs of radio emission spatially coincident with the TDG candidate HCG 91i (emission maxima matched with less than 150 pc separation) detected in H$_{i}$ line by Eigenthaler et al. (2015) both at 1.4 and 4.86 GHz. The detected emission has a steep spectrum, characterized by an index of $0.91 \pm 0.21$.

2. Analysis of the high-resolution 8.46 GHz and TGSS-ADR 150 MHz radio data yields no radio detection, suggesting that either the radio source is a Gigahertz-Peaked Source (or an aged AGN), or a star-forming region, weak at lower frequencies due to the absorption of synchrotron radiation on the thermal electrons, and resolved and thus too faint to be seen at 8.46 GHz.

3. Even after the H$_{i}$ luminosity is corrected for the dust attenuation (using upper constraints as no detection was made at 22 μm), SFRH$_{i}$, is about an order of magnitude lower than SFR$_{1.4 \text{GHz}}$.

4. Comparison of SFR$_{1.4 \text{GHz}}$ and SFRH$_{i}$ for a subset of starbursting dwarf galaxies shows that in most of the cases these two values are either concordant, or the difference can be attributed to the accuracy of the measurement, with the single exception of SQ–A TDG candidate, where SFRH$_{i}$ is significantly higher than its SFR$_{1.4 \text{GHz}}$ (and HCG 91i, if the radio emission is intrinsic to it).

5. Analysis of the stellar content and SFR versus stellar mass relation suggests that both HCG 91i and SQ–A are massive objects, and their expected SFR values are of the order of $1M_{\odot}$ yr$^{-1}$; hence, in case of the former object, it is the radio estimate that seems to be more feasible.

6. Ultraviolet star formation rates, even when corrected for the dust attenuation, are very low, thus ruling out the possibility that the discrepancy between different SFR indicators is due to a burst of star formation.

7. At the moment, the scenario in which HCG 91i is a former star-forming region of its parent galaxy, with the radio emission being a remnant of this evolutionary stage, seems to fit the observations (and estimations) the best.

8. Should the radio emission originate in HCG 91i, then the derived strength of the magnetic field inside is $11–16 \mu G$, similar to that found in starburst dwarf galaxies, or disk regions of vigorous star formation.

9. If this is not the case, then the upper constraints for the strength of the magnetic field inside all of the TDG candidates in the studied systems vary from 6 to 8 μG, leaving a possibility that strong magnetic fields can still be left undetected.

I would like to thank the anonymous referee for a number of comments and suggestions that helped to significantly improve this paper. I am also indebted to Krzysztof Chyży, Marek Jamrozy, and Marian Soida from the Astronomical Observatory of the Jagiellonian University for useful comments and suggestions that also helped to improve this paper.
The Astrophysical Journal, 885:107 (10pp), 2019 November 10

ORCID iDs
Błażej Nikiel-Wroczyński @ https://orcid.org/0000-0002-2470-012X

References
Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2007, ApJS, 175, 297
Beck, R., & Krause, M. 2005, AN, 326, 414
Beck, R., & Wielebinski, R. 2013, in Stars and Stellar Systems, Vol. 5: Galactic Structure and Stellar Populations, ed. G. Gilmore (Berlin: Springer)
Bournaud, F. 2010, in ASP Conf. Ser. 423, Galaxy Wars: Stellar Populations and Star Formation Interacting Galaxies, 2010 ed. B. Smith et al. (San Francisco, CA: ASP), 177
Bournaud, F., Duc, P.-A., Amram, P., Combes, F., & Gach, J.-L. 2004, A&A, 425, 813
Brinks, E., Duc, P.-A., Amram, P., Combes, F., & Gach, J.-L. 2004, A&A, 425, 813
Chyży, K. T., Beck, R., Kohle, S., Klein, U., & Urbanik, M. 2000, A&A, 355, 128
Chyży, K. T., Weżgowiec, M., Beck, R., & Bomans, D. J. 2011, A&A, 529, 94
Condon, J. J. 1992, ARA&A, 30, 575
Condon, J. J., Cotton, W. D., & Broderick, J. J. 2002, AJ, 124, 675
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, ApJ, 115, 1693
Duc, P.-A., Braine, J., Lisenfeld, U., Brinks, E., & Boquien, M. 2007, A&A, 475, 187
Eigenthaler, P., Ploeckinger, S., Verdugo, M., & Ziegler, B. 2015, MNRAS, 451, 2793
Eskew, M., Zaritsky, D., & Meidt, S. 2012, AJ, 143, 139
Hao, C.-N., Kennicutt, R. C., Johnson, B. D., et al. 2011, ApJ, 741, 124
Heesen, V., Brinks, E., Leroy, A. K., et al. 2014, AJ, 147, 103
Hickson, P. 1982, ApJ, 255, 382
Hickson, P., Mendes de Oliveira, C., Huchra, J. P., et al. 1992, ApJ, 399, 353
Hunsberger, S. D., & Zaritsky, D. 1996, ApJ, 462, 50
Intema, H. T., Jagannathan, P., Mooley, K. P., & Frail, D. A. 2016, A&A, 598, 78
Kaviraj, S., Darg, D., Lintott, C., Schawinski, K., & Silk, J. 2012, MNRAS, 419, 70
Kennicutt, R. C., & Evans, N. J. 2012, ARA&A, 50, 531
Kepley, A. A., Mühle, S., Everett, J., et al. 2010, ApJ, 712, 536
Kroupa, P. 2001, MNRAS, 322, 231
Lacki, B. C., & Beck, R. 2013, MNRAS, 430, 317
Lisenfeld, U., Braine, J., Duc, P. A., et al. 2016, A&A, 590, 92
Makarov, D., Prugniel, P., Terekhova, N., Courtois, H., & Vauglin, I. 2014, A&A, 570, 13
Makarova, L. N., Grebel, E. K., Karachentsev, I. D., et al. 2002, A&A, 396, 473
McQuinn, K., Skillman, E. D., Cannon, J. M., et al. 2010, ApJ, 721, 297
Mirabel, I. F., Dottori, H., & Lutz, D. 1992, A&A, 256, 19
Murphy, E. J., Condon, J. J., Schinnerer, E., et al. 2011, ApJ, 737, 67
Nikiel-Wroczyński, B., Janrozy, M., Soida, M., Urbanik, M., & Knapik, J. 2016, MNRAS, 459, 683
Nikiel-Wroczyński, B., Soida, M., Bomans, D. J., & Urbanik, M. 2014, ApJ, 786, 144
Nikiel-Wroczyński, B., Soida, M., Urbanik, M., Beck, R., & Bomans, D. J. 2013a, MNRAS, 435, 149
Nikiel-Wroczyński, B., Soida, M., Urbanik, M., et al. 2013b, A&A, 553, 33
Niklas, S. 1995, PhD thesis, Univ. Bonn
O’Dea, C. P., Baum, S. A., & Stanghellini, C. 1991, ApJ, 380, 660
Salpeter, E. E. 1955, ApJ, 121, 161
Stéphan, É. J.-M. 1877, MNRAS, 37, 334
Weiler, K. W., & Sramek, R. A. 1988, ARA&A, 26, 295
Weżgowiec, M., Soida, M., & Bomans, D. J. 2012, A&A, 544, 113
Xu, C. K., Lu, N., Condon, J. J., Dopita, M., & Tuffs, R. J. 2003, ApJ, 595, 665
Zwicky, F. 1956, ErNW, 29, 344