Intergalactic magnetic fields in Stephan’s Quintet

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Accepted 2013 July 4. Received 2013 July 2; in original form 2013 March 13

ABSTRACT

We present the results from the Very Large Array radio continuum total power and polarized intensity observations of Stephan’s Quintet at 1.43 and 4.86 GHz, along with complementary 4.85- and 8.35-GHz Effelsberg observations. Our study shows a large envelope of radio emission encompassing all the member galaxies and hence a large volume of intergalactic matter. Infall of the galaxy NGC 7318B produces a ridge of intergalactic, polarized emission, for which the magnetic field strength has been estimated as 11.0 ± 2.2 μG, with an ordered component of 2.6 ± 0.8 μG. The energy density of the field within the ridge area is of the same order as estimates of the thermal component, implying that the magnetic field has a significant role in the dynamics of the intergalactic matter. We also report that the tidal dwarf galaxy candidate SQ-B possesses a strong and highly anisotropic magnetic field, with a total strength equal to 6.5 ± 1.9 μG and an ordered component reaching 3.5 ± 1.2 μG, which is comparable to that found in normal-sized galaxies.

Key words: polarization–galaxies: groups: individual: HGC 92 (Stephan’s Quintet)–galaxies: interactions–intergalactic medium–galaxies: magnetic fields–radio continuum: galaxies.

1 INTRODUCTION

Intergalactic magnetic fields are among the least studied phenomena related to galaxy groups. So far, only a limited sample of such objects has been studied at radio wavelengths. All these studies (e.g. Xu et al. 2003; Giacintucci et al. 2012) have focused on the total power (TP) emission, not taking into account the polarized intensity (PI).

The detection of intergalactic polarized emission is an important issue. Polarization is caused by magnetic fields that show some degree of ordering. This could mean either genuinely unidirectional fields (called ‘regular’ fields, with no reversals of lines) or squeezed/stretching random fields (called ‘anisotropic’ fields), which have a preferred direction of fluctuations but frequent reversals. The existence of a unidirectional field suggests that it originated in galaxies hosting large-scale dynamos. Such a magnetic field is recognized by non-zero Faraday rotation measures (RMs), while a lack of measurable RMs indicates the generation of a twisted magnetic field, possibly compressed by intergalactic shocks (Chyży et al. 2000). The discrimination is possible by determining the RMs via multifrequency polarization observations or by using the RM synthesis method (Brentjens & de Bruyn 2005). Moreover, the polarized emission provides an extremely sensitive tool to reveal possible gas compression and shearing flows, which cause the magnetic field to be aligned along the compression front and/or perpendicular to the velocity gradients (Urbanik 2005; Wężykowicz et al. 2012).

Stephan’s Quintet (located approximately 85 Mpc from the Milky Way; Hickson et al. 1992) is one of several galaxy groups that possibly host intergalactic magnetic fields, and is known for magnificent dust tails emerging from NGC 7319. Additionally, it contains a radio ridge produced by the interactions with infalling NGC 7318B galaxy (Xu et al. 2003), as well as a large-scale HI tail overlapping the interloper galaxy NGC 7320 (Williams, Yun & Verdes-Montenegro 2002).

Since its discovery in 1877, Stephan’s Quintet, named after its discoverer Édouard Jean-Marie Stephan, has been subject to extensive, multiwavelength studies, much more detailed than for any other compact group. Denoted HCG 92 (Hickson 1982), the group is known to exhibit numerous interaction-related phenomena, such as changes in the morphology of the galaxies, starburst activity (Xu et al. 2003), gas outflows visible in various regimes (Williams et al. 2002; Xu et al. 2003; Guillard et al. 2012; Natalie et al. 2012) and possible shock compression (Appleton et al. 2006; O’Sullivan et al. 2009). The group is also clearly visible in radio continuum (Williams et al. 2002), and a careful study of the data from the New Very Large Array (VLA) Sky Survey (NVSS) shows some evidence for polarized emission at 1.4 GHz (Condon et al. 1998).
Several radio continuum studies of Stephan’s Quintet and its member galaxies have been performed since 1972 (Allen & Hart- suker 1972; Arp 1972). The most recent are the high-resolution study of the active galactic nuclei in NGC 7319 (Aoki et al. 1999) and that of the extended emission at 1.43 and 4.86 GHz by Xu et al. (2003), who have presented images of the TP emission, made using the VLA interferometer in its B and C configurations. These images show a large-scale radio emitting ridge between NGC 7318B and 7319 at both wavelengths, coincident with an ultraviolet (UV) emitting region and X-ray features (as presented by Trinchieri et al. 2003, 2005; O’Sullivan et al. 2009). Their high-resolution configurations of the VLA caused a substantial flux loss, and most of the extended emission was not detected. Moreover, the weak polarized emission (marginally visible in the NVSS map) remained undetected.

Recently, Geng et al. (2012) have simulated the distribution of the magnetic field (together with the X-ray morphology) of Stephan’s Quintet. Both models (from Renaud, Appleton & Xu 2010 and from Hwang et al. 2012) adapted by Geng et al. (2012) suggest a collisional origin for the shock region and a significant magnetic field between NGC 7319 and 7318B.

In this paper, we present observations of Stephan’s Quintet made using the VLA D-array, sensitive to the extended emission, with special attention paid to polarization. The observations were performed at two different frequencies: 1.43 and 4.86 GHz. Additionally, we made single-dish observations using the 100-m Effelsberg radio telescope at 4.85 and 8.35 GHz.

### 2 OBSERVATIONS AND DATA REDUCTION

#### 2.1 Interferometric observations

The 4.86-GHz data were obtained in 2008 August using the VLA of the National Radio Astronomy Observatory (NRAO)\(^1\) in the D-array configuration. The total on-source time (TOS) was 21.5 h. The 1.43-GHz data were also acquired using the D-array, with a TOS of 4 h. Moreover, we were granted 3.5 h in dynamic time allocation mode (CD- and D-arrays), obtained between 2007 February and April. In both cases, the bandwidth was 2 × 50 MHz, centred at 4835 and 4885 MHz in the C-band, and 1385 and 1465 in the L-band.

The data were reduced using the Astronomical Image Processing System (AIPS) and calibrated using 3C 48 at 1.43 GHz and 3C 286 at 4.86 GHz as the flux and polarization position angle calibrators. The nearby point source 2236+284 was used as a phase and instrumental polarization calibrator. For the 4.86-GHz data, we made a set of Stokes $I$, $Q$ and $U$ maps using Briggs weighting (robust parameter = 3), yielding a beam size of $13.65 \times 12.28$ arcsec. These maps were later convolved to a circular beam of 20 arcsec. We have also produced a uniformly weighted map of the Stokes $I$ channel, with a beam of 6.8 arcsec. The lower-resolution set was used to produce distributions of diffuse TP and PI emission, while the uniformly weighted map shows details of the TP emission. At 1.43 GHz, maps in all Stokes parameters were convolved to a common beam of 42 arcsec. Finally, the $U$ and $Q$ maps at both frequencies were combined to yield the distributions of PI and polarization angle.

#### 2.2 Single-dish observations

Single-dish mapping of Stephan’s Quintet was performed using the 100-m radio telescope at Effelsberg.\(^2\) Observations were performed at 8.35 GHz, using a single-beam receiver installed in the secondary focus of the telescope. The bandwidth was 1.1 GHz and the final resolution (after some convolution) is 85 arcsec. In order to produce the final map, 27 coverages were obtained, each of size $16 \times 16$ arcmin\(^2\), scanned alternatively along RA and Dec. The scanning velocity was 30 arcsec s\(^{-1}\) and the grid spacing was 30 arcsec. All coverages were combined in the Fourier domain to reduce the scanning effects (Emerson & Gräve 1988), for the Stokes parameters $I$, $Q$ and $U$ separately. Again, we obtained maps of the PI and polarization angle from our combined $U$ and $Q$ data. The flux density scale was established using the source 3C 286, according to the flux values given by Baars et al. (1977). Additional 4.85-GHz mapping has also been performed in order to provide the zero-spacing information that is missing in the interferometric data. These complementary single-dish observations yielded no larger integrated total flux, indicating that there were no flux losses in the interferometric data. Thus, no merging was performed.

Because the uncertainties of the flux values based on the rms noise levels have turned out to be small compared to the uncertainties of the calibration, we assume a 5 per cent error for each integrated flux value for the radio maps. The noise levels obtained for all radio maps are presented in Table 1.

### Table 1. Noise levels ($\sigma$) obtained in the final TP and PI maps.

| Frequency (GHz) | $\sigma$ (TP) ($\mu$Jy beam\(^{-1}\)) | $\sigma$ (Stokes $Q$ and $U$) ($\mu$Jy beam\(^{-1}\)) | $\sigma$ (PI) ($\mu$Jy beam\(^{-1}\)) | Beam size (arcsec) | Telescope/Configuration |
|---------------|-------------------------------|-------------------------------------------------|---------------------------------|-------------------|------------------------|
| 8.35          | 100                           | 48                                              | 54                              | 71                | 85                     | Effelsberg             |
| 4.86          | 6                             | 6                                               | 6                               | 6                 | 20                     | D-array                |
| 1.43          | 110                           | 22                                              | 24                              | 32                | 42                     | CD- and D-array        |

\(^{1}\) NRAO is a facility of the National Science Foundation, operated under cooperative agreement by the Associated Universities, Inc.

\(^{2}\) Based on observations with the 100-m telescope of the Max-Planck-Institut für Radioastronomie (MPIfR) at Effelsberg.
3 RESULTS

In this paper, we use the term ‘apparent polarization B-vectors’, defined as the observed polarization E-vector direction rotated by 90°, uncorrected for the Faraday rotation, except for the maps in Section 4.

3.1 Total power emission at 4.86 GHz

The TP maps of HCG 92 at 4.86 GHz are shown in Figs 1 and 2. The high-resolution map, with a half-power beam width (HPBW) of 6.8 arcsec, shows two bright point sources and some extended emission.

The most important structure in this study is the intergalactic emission ridge located between the galaxies that form the group, near RA$_{2000}$ = 22°36′00″ and Dec$_{2000}$ = +33°57′30″. In the observations by Xu et al. (2003), the structure of the ridge is similar to the one presented in Fig. 1. By integrating the flux within the same boundaries, we have obtained 10.6 ± 0.6 mJy, which is very similar to their value of 10.9 ± 1.1 mJy.

The brightest source in the map (located at RA$_{2000}$ = 22°36′04″, Dec$_{2000}$ = +33°58′33″) is the core of the Seyfert type 2 galaxy NGC 7319. The core is barely resolved and its flux of 9.38 ± 0.49 mJy agrees with the value given by Aoki et al. (1999).

The 0.61 ± 0.03 mJy peak at RA$_{2000}$ = 22°35′57″, Dec$_{2000}$ = +33°57′55″ is the core of NGC 7318A. The flux is higher than that presented by Xu et al. (0.44 ± 0.03 mJy), which might indicate the presence of an extended structure or variability.

In the northern part of the group, a strong point source can be seen near RA$_{2000}$ = 22°36′00″, Dec$_{2000}$ = +33°59′12″. This peak represents an unresolved double radio source, denoted SQ-R by Xu et al. (2003), most probably unrelated to the group. Our 4.86-GHz total flux of 4.0 ± 0.2 mJy remains in very good agreement with the value of 3.7 ± 0.4 mJy obtained by Xu et al. (2003).

South of SQ-R, a weak peak near RA$_{2000}$ = 22°35′56″ and Dec$_{2000}$ = +33°59′20″ represents the SQ-A starburst region. Its flux of 0.32 ± 0.02 mJy is in excellent agreement with 0.3 ± 0.1 mJy obtained by Xu et al. (2003).

More extended emission can be seen in the lower-resolution map (Fig. 2). The second starburst region, SQ-B (which is likely to be a part of the tidal arm – a remnant of the past interactions with NGC 7320C), located at RA$_{2000}$ = 22°36′10″, Dec$_{2000}$ = +33°57′22″, has an integrated flux of 0.16 ± 0.01 mJy, which is similar to the value given by Xu et al. (0.2 ± 0.1 mJy). A comparison with our uniformly weighted map (Fig. 1) shows the presence of the extended, diffuse emission in that region.

In the southern part of the group, the diffuse emission terminates near the outskirts of the interloper galaxy NGC 7320. The H I emission studies by Williams et al. (2002) show that the southern part of the group is connected to an H I tail, extending eastwards from the group and containing the SQ-B starburst region. Unfortunately, our map does not allow a reliable discrimination of whether or how the radio emission is connected to the interloper galaxy (this issue is discussed in Section 4.1.4).

The envelope of diffuse emission has an extension towards the western edge, which has no counterpart in the optical regime. The extension is located near RA$_{2000}$ = 22°35′53″, Dec$_{2000}$ = +33°58′30″. The lower-resolution map shows another extension – towards the eastern part of the group, overlapping the spiral arm of NGC 7319.

3.2 Distribution of the polarized intensity at 4.86 GHz

Fig. 3 shows the contours of the PI distribution overlaid on a grey-scale optical image, with the apparent B-vectors proportional to the polarization degree. The most prominent structure is the emission ridge with a mean polarization degree of around 4–5 per cent. The ridge is a part of an extended structure, also filling a large volume between NGC 7318A and 7319 as well as containing the SQ-R source. The polarization degree of the latter is approximately 3 per cent.

Whereas the core of NGC 7319 and the galaxy itself seem to be unpolarized, the core of NGC 7318A is present in the PI.
Figure 3. Briggs weighted contour map of the PI distribution of Stephan’s Quintet at 4.86 GHz with apparent B-vectors of the PI overlaid upon an SDSS-R image. The contour levels are −3 (dashed), 3, 5, 10 and 20 × 6 µJy beam$^{-1}$ (rms noise level). A polarization vector of 1 arcsec corresponds to a polarization degree of 0.5 per cent. The angular resolution of the map is 20 arcsec.

distribution map, with a polarization degree of approximately 6 per cent (averaged over the central area). The 4.86-GHz PI distribution also shows a large pool of polarized emission north from the ridge. The western extension of the TP envelope is also visible in our PI map.

East of the group, a spot of polarized emission spatially coincident with SQ-B can be seen. The polarization fraction of this source reaches 33 per cent.

3.3 Total power and polarized emission at 1.43 GHz

Fig. 4 shows the TP map of HCG 92 at 1.43 GHz with superimposed apparent polarization B-vectors. The resolution is consider-

ably lower and this enables us to trace the emission further out. Two point sources can easily be distinguished from the surrounding emission: the core of NGC 7319 and SQ-R. The flux of the first, estimated by a Gaussian fit centred on the galactic core, is 32 ± 2 mJy, which is therefore slightly higher than 28.5 mJy as given by Aoki et al. (1999) and Xu et al. (2003).

Polarized emission from the ridge has not been detected at this frequency. Instead, weak emission is present in the tidal tail of NGC 7319. However, because of large depolarization (Section 4.2), we were unable to produce sufficiently reliable maps of the PI.

3.4 Total power and polarized emission at 8.35 GHz

Fig. 5 shows the TP emission distribution at 8.35 GHz. Despite the lower resolution (compared to the VLA), we can easily see that the total emission contours correspond fairly well to those seen at 1.43 and 4.86 GHz. The polarized emission exceeds the 3σ rms level only at distinct regions in the group area, such as between NGC 7319 and 7318A.

The strong and polarized background source J223552+335425, located south of Stephan’s Quintet, was used to determine the foreground RM. The best $\lambda^2$ fit to the polarization angles of this source at all three frequencies (1.43, 4.86 and 8.35 GHz) yields a RM of 182 rad m$^{-2}$, which agrees well with the values measured in the vicinity of the group (Taylor, Stil & Sunstrum 2009). With a value of 182 rad m$^{-2}$, the polarization angle is rotated more than 360° at 1.43 GHz, 40° at 4.86 GHz and no more than 14° at 8.35 GHz.
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4 DISCUSSION

4.1 Spectral index

In order to calculate the spectral index distribution, we have added to our 1.43-GHz observations, the data sets obtained by Xu et al. (2003) in the VLA B-configuration at the same frequency, taken from the NRAO archive. By combining all available data at 1.43 GHz, we obtain maps with similar resolution as at 4.86 GHz. Maps at both frequencies were convolved with a Gaussian function to obtain a final circular beam with a HPBW of 20 arcsec (small enough to distinguish point-source emission from the extended emission). An additional map, with a beam of 42 arcsec, has been made in order to provide information about the regions of weak, diffuse emission, not visible in the high-resolution map. The spectral index distribution is shown in Fig. 6. Throughout the paper, we use the $S_\nu \propto \nu^{-\alpha}$ definition of the spectral index $\alpha$.

4.1.1 Point sources

The spectral index of the core of NGC 7319 (approximately $0.83 \pm 0.07$) is, within errors, consistent with the value given by Xu et al. (2003). The lower-resolution map also allows us to compute the spectral index in the area of the spiral arm, where $\alpha = 0.95 \pm 0.04$, which is a reasonable value for galactic synchrotron emission.

The resolution of 20 arcsec is high enough to measure the spectral index for the background source SQ-R. The value of $0.81 \pm 0.09$ agrees very well with the value of $0.85 \pm 0.12$ given by Xu et al. (2003).

The core of NGC 7318A is surrounded by steep-spectrum emission. The spectral index derived for the region close to the peak of the emission is $1.1 \pm 0.1$, which is substantially higher than the value given by Xu et al. (0.62 \pm 0.07), possibly indicating the presence of a diffuse, steep-spectrum component in our 1.43-GHz map.

4.1.2 Star formation regions

The SQ-B region is marginally visible in the high-resolution map, but it can be clearly seen in the lower-resolution image. The spectral index of this region is approximately $1.2 \pm 0.2$, a value that is higher than the value of $0.7 \pm 0.4$ measured by Xu et al. (2003), but still within the measurement uncertainties. Our low-resolution TP map shows more extended diffuse emission. Because the beam is about three times larger than in the study cited, the integrated flux value now not only represents the point source, but also has a contribution from the diffuse structure around. A diffuse, steep-spectrum emission ($\alpha = 1.4$) contribution of about 50 per cent in our larger beam map would explain the difference.

The area of the flatter spectrum within the intergalactic emission, which is spatially correlated with the SQ-A region, can be distinguished from the surrounding emission only in the high-resolution map. The value obtained for the region ($1.1 \pm 0.1$) is higher than that given by Xu et al. (0.8 \pm 0.3), but, as in the case of SQ–B, within the given uncertainties. Again, this might be a result of a contamination of the extended, steep-spectrum emission, as in the case of SQ-B.

4.1.3 Intra-group emission

The emission ridge is clearly visible in both the high- and low-resolution maps. The spectrum steepens from approximately 0.85 near the southern boundaries to 1.1–1.3 in the central part. The mean spectral index of this region is equal to $1.1 \pm 0.15$ and is consistent, within errors, to the value obtained by Xu et al. (0.93 \pm 0.13).

The 20-arcsec resolution is sufficient to separate the point sources from the diffuse emission, allowing us to determine the spectral index. The values vary from 1.3 in the central part to 1.8 in the outskirts, and are typical for an ageing population of synchrotron electrons.
The western extension coincides with a region that shows a significantly steeper spectrum than the rest of the radio emission (Fig. 3). The spectral index $\alpha$ of this region is 1.4 ± 0.2 GHz, which is significantly higher than the other regions that show a more steepening spectrum. This high-index region is connected to the vectors overlapping the shock area. The vectors form an arc bending in the eastern direction, matching the Hα emission from the shock. The analysis of the spectral index of this region shows a significant difference from the rest of the group, suggesting a possible past interaction within the group. The inclination of the NGC 7320 is approximately 60°, which could be a projection of the magnetic field lines of the foreground galaxy.

### 4.1.4 Hα tail or an interloper galaxy?

The low-resolution map (Fig. 6, right panel) was made to visualize the spectral index of the diffuse emission regions, which have a surface brightness that is too low to be visible in the high-resolution map. One of these is the southern extension, where the Hα tail overlaps the galaxy NGC 7320 (Williams et al. 2002). The measured $\alpha$ of approximately 0.9 ± 0.1 GHz for this region is significantly lower than the typical values for diffuse emission regions in the intergalactic medium (IGM). This suggests that the emission is related to the star-forming interloper galaxy rather than to an intergalactic structure. The polarized fraction of this region reaches 13 per cent, which is consistent with the observed spectral index.

### 4.2 Faraday depolarization

Because the PI distribution map at 1.43 GHz shows very weak polarization (see Section 3.3), we used the term ‘depolarization’ to define $DP = 1 - p_{1.43}/p_{4.86}$, where $p$ refers to the polarization degree at a given frequency. Both maps were made with the same beam size, such a definition makes this parameter independent of beam depolarization. The mean depolarization of the radio-emitting envelope between 1.43 and 4.86 GHz is equal to 0.84. In contrast, the background source J223552+335425 shows depolarization of only 40 per cent. The exact values can be affected by differences in the bandwidth depolarization at both frequencies, but this effect cannot affect the variation of $DP$ with position in the map. These values indicate that the depolarization caused by the foreground Faraday dispersion is not likely to explain the high degradation of the polarized emission estimated for Stephan’s Quintet. The alternative explanation is that the depolarization in the group is caused either by Faraday rotation inside Stephan’s Quintet or by internal Faraday dispersion. The first possibility is that the intergalactic space in Stephan’s Quintet hosts a substantial unidirectional dynamo-type magnetic field. However, the present data do not allow us to disregard the scenario of depolarization via Faraday dispersion. Moreover, there is a possibility that the depolarization estimate for the background source is influenced by its internal depolarization. Furthermore, the foreground depolarization distribution might be patchy. The RM synthesis method (as described by Brentjens & de Bruyn 2005) will probably be able to distinguish between these two mechanisms, but it needs much better frequency coverage and higher resolution than those offered by the existing data.

### 4.3 Magnetic field strengths in Stephan’s Quintet

The strength of the magnetic field and its energy density were calculated from the 4.86-GHz data, assuming energy equipartition between the cosmic rays and the magnetic field, following the formulae presented by Beck & Krause (2005). Table 3 presents the chosen values of the parameters (the total path-length $D$, the proton-to-electron energy density ratio $K_0$, the spectral index $\alpha$, the 4.86-GHz flux $S_{4.86}$ and the polarization degree $p$) for each of the regions. This table also contains the calculated total and ordered field strength, as well as the magnetic field energy density in each case.
4.3.1 Magnetic field in the ridge

The path-length $D$ through the ridge was estimated to be 10–15 kpc (based on the size of the shock region from the high-resolution radio map and assuming cylindrical symmetry). The flux and spectral index were taken from our VLA data. Because the spectrum is relatively steep, the thermal fraction contribution is negligible. The problem arises with the value of the $K_0$ coefficient. Its value depends on the strength of a shock, and for strong shocks (compression ratio $r \geq 3.4$) $K_0$ reaches 40–100. Assuming $K_0 = 100 \pm 50$, the total magnetic field strength in the ridge is $11.0 \mu G \times (K_0/100)^{0.244} \pm 2.2 \mu G$ with an ordered component of $2.6 \pm 0.8 \mu G$. However, it is not certain whether the shock in Stephan’s Quintet is a strong or a weak shock, because weak shocks would also be able to produce the observed X-ray properties of the group (see O’Sullivan et al. 2009, section 5.3, for a detailed discussion). In that case, the $K_0$ value would be much higher (even by several orders of magnitude). For relatively weak shocks ($r \leq 2.2$), the magnetic field strength would increase more than three times.

The total magnetic energy density of the shock area is estimated as $E_B = 0.5 \pm 0.15 \times 10^{-11}$ erg cm$^{-3}$. The thermal energy of the shock area is estimated from the X-ray data using the temperature of 0.6 keV and gas density of $1.167 \times 10^{-3} \text{cm}^{-3}$ taken from O’Sullivan et al. (2009), yielding a value of $\approx 1.1 \times 10^{-11}$ erg cm$^{-3}$. This means that the magnetic field plays an important role in the dynamics of the IGM, contrary to the statement by Xu et al. (2003). Its contribution to the total energy, comparable to the thermal component, proves that it is necessary to take the magnetic field into account while performing simulations of the intra-group medium.

4.3.2 Magnetic field in the tidal dwarf galaxy

Stephan’s Quintet is known to be a host group for at least 13 tidal dwarf galaxy (TDG) candidates, located in the tidal tail connected to NGC 7319 (Hunsberger, Charlton & Zaritsky 1996). One of these is the star formation region SQ-B. For SQ-B, we have calculated the properties of the magnetic field under the assumption that the $K_0$ ratio is equal to 100, because we do not expect the field to be produced by secondary electrons or shocks (see Beck & Krause 2005 for details). The total path-length through the emitting volume was chosen to be equal to 6 ± 3 kpc. The flux and spectral index were taken from our VLA data. Because the spectrum is relatively steep (1.2 ± 0.2), the thermal fraction contribution is negligible.

The magnetic field of the TDG candidate is relatively strong ($\approx 6.5 \mu G$), similar to those found in normal-sized spiral galaxies, for which the median value is $9 \pm 1.3 \mu G$ (Niklas 1995). The ordered component (reaching 3.5 ± 1.2 $\mu G$) is also significant, because the polarization degree is substantial (33 per cent).

The strength of the magnetic field and its anisotropy suggest an in situ amplification of the field in the TDG candidate. The presence of the star formation and the shearing flow of infalling plasma debris left by the passage of NGC 7320C can efficiently amplify the magnetic field, even if we assume a low mass and slow rotation of a dwarf galaxy (Siekowska et al. 2010). Given that the plasma debris is likely to have already been magnetized, the amplification process could result in values as high as those in normal galaxies.

The second starburst region, SQ-A, lies inside an extended polarized region. Hence, it cannot be distinguished from the surrounding emission. The total magnetic field strength of this region is estimated to be 8.8 ± 2.3 $\mu G$. This translates into a magnetic field energy density of $3.0 \pm 1.6 \times 10^{-12}$ erg cm$^{-3}$.

4.3.3 Mean magnetic field in the group area

In order to estimate the mean magnetic field in the group area, we have subtracted the point sources (from Aoki et al. 1999) and the ridge area, and then clipped the resulting map at the level of approximately 8$\sigma$ to obtain the integrated flux of the group. The path-length was adopted as equal to the separation between the galaxies originally forming Stephan’s Quintet (NGC 7317, 7318A and 7319), and $K_0$ was adopted as 100. The spectral index was taken from our VLA data. Because the spectrum is relatively steep, we decided to neglect the thermal flux contribution. We estimated the strength of total magnetic field to be $6.4 \pm 1.1 \mu G$ with an ordered component of $1.1 \pm 0.3 \mu G$, indicating an energy density of $1.8 \pm 0.5 \times 10^{-12}$ erg cm$^{-3}$. The magnetic field in the intergalactic space is of similar strength as in the star-forming regions SQ-A and SQ-B.

4.3.4 Shock compression as a possible origin of the magnetic field in the ridge

The emission ridge has been studied extensively in different regimes of the electromagnetic spectrum (see references in Section 1). Three mechanisms explaining the observed properties of the ridge have been described and then tested for Stephan’s Quintet, the proposed mechanisms being the accretion of the primordial gas (Osmond & Ponman 2004; O’Sullivan et al. 2009), the heating of the medium by high-mass X-ray binaries and supernovae (O’Sullivan et al. 2009) and shock heating (Appleton et al. 2006; O’Sullivan et al. 2009). The latter was suggested as the most probable, providing the most accurate explanation of the observed energy and temperature distributions of the X-ray emitting medium, as well as explaining phenomena seen in other regimes of the electromagnetic spectrum. The study of the magnetic field can provide arguments for or against the shock scenario, because propagation of the shock waves through the magnetized plasma should result in a change in the orientation of the magnetic field; in particular, the magnetic field can thus be squeezed, resulting in a higher polarization degree (Urbanik 2005). Because the emission ridge is expected to be formed by means of shocking the IGM as a result of the high-speed infall of NGC 7318B to the group, there should be a polarized structure between the galaxies mentioned above. In Fig. 7, the TP emission contours and B-vectors of the PI, corrected for the foreground Faraday rotation, from our 4.86-GHz observations have been overlaid upon the Chandra image presenting the X-ray emission. The area of the shock agrees well with the polarized radio ridge, with the maximum located near

| Region | $D$ (kpc) | $K_0$ | $\alpha$ | $S_{8_06}$ (mJy) | $p$ (per cent) | $B_{TOT}$ ($\mu G$) | $B_{ORD}$ ($\mu G$) | $E_B$ (erg cm$^{-3}$) |
|--------|----------|-------|----------|----------------|--------------|-----------------|-----------------|------------------|
| Ridge  | $12.5 \pm 2.5$ | $100 \pm 50$ | $1.1 \pm 0.15$ | $10.6 \pm 0.6$ | $5$ | $11.0 \pm 2.2$ | $2.6 \pm 0.8$ | $0.5 \pm 0.15 \times 10^{-11}$ |
| SQ-A   | $6 \pm 3$ | $100$ | $1.1 \pm 0.1$ | $0.32 \pm 0.02$ | $-$ | $8.8 \pm 2.3$ | $-$ | $3.0 \pm 1.6 \times 10^{-12}$ |
| SQ-B   | $6 \pm 3$ | $100$ | $1.2 \pm 0.2$ | $0.16 \pm 0.01$ | $33$ | $6.5 \pm 1.9$ | $3.5 \pm 1.2$ | $1.8 \pm 0.9 \times 10^{-12}$ |
| Group  | $32 \pm 6$ | $100$ | $1.2 \pm 0.2$ | $4.6 \pm 0.6$ | $2$ | $6.4 \pm 1.1$ | $1.1 \pm 0.3$ | $1.8 \pm 0.5 \times 10^{-12}$ |
the southern end of the X-ray ridge, which indicates an increased polarization degree of the IGM in that region. Because the shock is clearly visible in the UV data, we have superimposed the Galaxy Evolution Explorer (GALEX) near-UV image of Stephan’s Quintet with the polarization B-vectors (corrected for the foreground foreground RM) at 4.86 GHz (Fig. 8). The orientation of the vectors (parallel to the shock) strongly supports the idea of an enhancement of the anisotropy because of shock-driven compression.

4.3.5 Magnetic field as a tracer of the previous interactions

Fig. 3 shows an extended area of enhanced polarization degree between the radio ridge and NGC 7319 (near RA$=22^\text{h}36^\text{m}00^\text{s}$, Dec$=+33^\circ58'20'\prime$). The polarized fraction is significant, ranging from approximately 6 per cent near the ridge up to 13 per cent in the outskirts of the western spiral arm of NGC 7319. The magnetic field, represented by the B-vectors (corrected for the foreground Faraday rotation of 182 rad m$^{-2}$, as seen in Fig. 8) seems to connect NGC 7319 with the pair NGC 7318A/B. The low-resolution map of the spectral index (Fig. 6, right panel) shows that $\alpha$ varies from approximately 1.2 to 1.8, with a mean value of 1.45 ± 0.15.

NGC 7319 is known to be perturbed by the previous interactions. It is usually suggested that they were the result of a hypothetical passage of NGC 7320C (Shostak, Allen & Sullivan 1984; Moles, Sulentic & Marquèz 1997; Moles, Marquèz & Sulentic 1998) that caused stripping of the material through the tidal tail containing SQ-B. However, NGC 7318A (as well as NGC 7317) is considered to be a non-interacting member of the group.

The diffuse emission with a steep spectrum and a high degree of polarization is likely to originate in the material stripped from NGC 7319, because this galaxy shows hardly any signs of the emission in $\text{H} \alpha$ (Shostak et al. 1984; Williams et al. 2002), $\text{H} \beta$ (Arp 1972; Moles et al. 1997) and CO (Yun et al. 1997). An active role of NGC 7318A in the previous interactions was first proposed by Shostak et al. (1984) and later supported by Xu et al. (2005), who proposed that the ‘UV loop’ structure connected to NGC 7319 might be a ‘counter-tidal’ tail formed during an encounter.

5 CONCLUSIONS

We have observed the Stephan’s Quintet group of galaxies using both the VLA at 1.43 and 4.86 GHz and the Effelsberg 100-m radio telescope at 4.85 and 8.35 GHz. We have obtained maps of TP emission and PI. These maps have been analysed together with the archive X-ray and UV data in order to explore the properties of the magnetic field in the group. We come to the following conclusions.

(i) The group has a large radio envelope, visible at 1.43, 4.86 and 8.35 GHz. The envelope encompasses all the member galaxies.

(ii) There is a narrow, S-shaped region of radio emission between the member galaxies. It extends from the background source at RA$=22^\text{h}36^\text{m}00^\text{s}$, Dec$=+33^\circ59'11''$ towards the shock region, and diminishes near the north-western edge of the foreground galaxy NGC 7320.

(iii) The mean polarization degree of the shock region is 5 per cent. The magnetic field strength obtained within this region is equal to 11.0 $\mu$G × (K/100)$^{0.244} \pm 2.2$ $\mu$G, with an ordered component of 2.6 ± 0.8 $\mu$G. The energy density of 0.5 ± 0.15 $\times 10^{-11}$ erg cm$^{-3}$ is comparable to that of the thermal component, indicating the dynamical importance of the magnetic field in the physics of the intra-group medium.

(iv) The radio emission from the aforementioned envelope is polarized, with a mean polarization degree of 2 per cent. The strength of the mean magnetic field within its boundaries is equal to 6.4 ± 1.1 $\mu$G, with an ordered component of 1.1 ± 0.3 $\mu$G. The average magnetic field energy density is 1.8 ± 0.5 $\times 10^{-12}$ erg cm$^{-3}$.

(v) The depolarization of the emission from Stephan’s Quintet calculated from the 1.43- and 4.86-GHz data exceeds 80 per cent. This is more than two times higher than the depolarization of the neighbouring background source. Such a difference suggests depolarization of the emission from the group either by intrinsic (within the emitting region) Faraday rotation or internal Faraday dispersion. In the first case, it would indicate the presence of a regular magnetic field.

(vi) The intergalactic emission has a rather steep spectrum, with a mean spectral index of 1.2 ± 0.2 between 1.43 and 4.86 GHz, and 1.7 ± 0.2 between 4.86 and 8.35 GHz. The steepness of the spectrum indicates that the intergalactic emission might be dominated by an ageing population of electrons and that the thermal component does not play a significant role.

(vii) There is a region of steep-spectrum (2.0 ± 0.2), highly (40 per cent) polarized emission on the north-western edge of the radio envelope. This region might be a remnant of the past interactions among the group members.

(viii) In the southern part of the group, the emission forms an extension overlapping the $\text{H} \alpha$ tail (detected by Williams et al. 2002). Although the orientation of the B-vectors seems to follow the $\text{H} \alpha$ tail, the spectral index of the emission (0.9 ± 0.1) indicates that it emerges not only from within the group, but also from the interloper galaxy NGC 7320. Moreover, the high inclination of NGC 7320 might result in projecting its magnetic field so that the B-vectors form an arc-like structure.

(ix) The radio emission from the starburst region SQ-B is substantially polarized (33 per cent), indicating the presence of a magnetic field with a total strength of 6.5 ± 1.9 $\mu$G and an ordered component reaching 3.5 ± 1.2 $\mu$G. Because this structure is supposed to be an example of a TDG, the detected field is likely to

Figure 8. Map of B-vectors of the PI at 4.86 GHz after the correction for the foreground Faraday rotation overlaid upon the near-UV image from GALEX. A polarization vector of 1 arcsec corresponds to a PI of 4.5 $\mu$Jy beam$^{-1}$. The clip limit for the vectors is 15 $\mu$Jy (2.5 × PI noise level). The angular resolution of the radio data is 20 arcsec. The ellipses mark the positions, sizes and orientations of discussed radio sources (taken from the HyperLeda data base). NGC 7320C lies approximately 1° away from the eastern boundary of this image.
be intrinsic to the dwarf, amplified by the flow of infalling magnetized plasma, stripped from the neighbour galaxy NGC 7319 during the passage of NGC 7320C.

ACKNOWLEDGEMENTS

We thank Kerstin Weis (Ruhr-Universität Bochum) and Marita Krause (MPIfR, Bonn) for valuable comments. This research has been supported by the scientific grant from the National Science Centre (NCN), DEC. no. 2011/03/B/ST9/01859. DJB and RB acknowledge support by the DFG SFB 591 'Universal Behaviour of Non-Equilibrium Plasmas' and DFG FOR 1254, 'Magnetization of Interstellar and Intergalactic Media'. This research has made use of 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 (NASA). This research has made use of NASA's Astrophysics Data System. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, NASA, the Japanese Monbukagakusho, the Max Planck Society and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/. This research has made use of data obtained from the Chandra Data Archive and of software provided by the Chandra X-ray Center (CXC) in the application packages CIAO, CHIPS and SHERPA. We acknowledge the use of GALEX.

REFERENCES

Allen R. J., Hartsuiker J. W., 1972, Nat, 239, 5371, 324
Aoki K., Kosugi G., Wilson A. S., Yoshida M., 1999, ApJ, 521, 565
Appleton P. N. et al., 2006, ApJ, 639, L51
Arp H., 1972, ApJ, 174, L111
Baars J. W. M., Genzel R., Pauliny-Toth I. I. K., Witzel A., 1977, A&A, 61, 99
Beck R., Krause M., 2005, AN, 326, 414
Brentjens M. A., de Bruyn A. G., 2005, A&A, 441, 1217
Chyży K. T., Beck R., Kohle S., Klein U., Urbanik M., 2000, A&A, 355, 128
Chyży K. T., Bomans D. J, Krause M., Beck R., Soida M., Urbanik M., 2007, A&A, 462, 933
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J, 1998, ApJ, 115, 1693

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