Multi-scale VLBI observations of the candidate host galaxy of GRB 200716C

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ABSTRACT

We present the discovery and the subsequent follow up of radio emission from SDSS J130402.36+293840.6 (J1304+2938), the candidate host galaxy of the gamma-ray burst (GRB) GRB 200716C. The galaxy is detected in the RACS (0.89 GHz), the NVSS, the Apertif imaging survey, and the FIRST (1.4 GHz), the VLASS (3 GHz), and in public LOFAR (130–170 MHz), WISE (3.4–22 μm), and SDSS (g, r, i, u) filters data. The luminosity inferred at 1.4 GHz is \( (5.1\pm0.2)\times10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1} \). To characterise the emission and distinguish between different components within the galaxy, we performed dedicated, high-sensitivity and high-resolution observations with the European VLBI Network (EVN) + e-MERLIN at 1.6 and 5 GHz. We did not detect any emission from a compact core, suggesting that the presence of a radio-loud active galactic nucleus (AGN) is unlikely, and therefore we ascribe the emission observed in the public surveys to star-forming regions within the galaxy. We confirm and refine the redshift estimate, \( z = 0.341\pm0.004 \), with a dedicated Telescopio Nazionale Galileo (TNG) spectroscopic observation. Finally, we compiled a list of all the known hosts of GRB afterglows detected in radio and computed the corresponding radio luminosity: if GRB 200716C belongs to J1304+2938, this is the third most radio-luminous host of a GRB, implying one of the highest star-formation rates (SFRs) currently known, namely \( \text{SFR} \approx 324\pm61 \text{ M}_\odot \text{ yr}^{-1} \). On the other hand, through the analysis of the prompt emission light curve, recent works suggest that GRB 200716C might be a short-duration GRB located beyond J1304+2938 and gravitationally lensed by an intermediate-mass black hole (IMBH) hosted by the galaxy. Neither the public data nor our Very Long Baseline Interferometry (VLBI) observations can confirm or rule out the presence of an IMBH acting as a (milli-)lens hosted by the galaxy, a scenario still compatible with the set of radio observations presented in this work.

Key words. radio continuum: general – gamma-ray burst: general – gamma-ray burst: individual: GRB 200716C – gravitational lensing: strong – techniques: high angular resolution – techniques: interferometric

1. Introduction

Gamma-ray bursts (GRBs) are cosmological explosions whose emission spans the whole electromagnetic spectrum, from soft γ-rays down to X-rays, optical/near-infrared (NIR), and radio (see e.g., Piran 2004). According to the \( T_{90} \) duration of their short-lived prompt emission, they are classified as short-duration (\( T_{90} < 2 \text{ s} \)) and long-duration GRBs (\( T_{90} \geq 2 \text{ s} \); Kouveliotou et al. 1993). This (apparently) arbitrary and crude separation has a deep connection with the progenitor’s nature of the burst: while short-duration GRBs flag the merger of two neutron stars or a neutron star and a black hole, as confirmed by the outstanding detection of the first multi-messenger event GW 170817/GRB 170817A (Abbott et al. 2017), long-duration GRBs are produced in the catastrophic explosion of massive single stars, as confirmed by many long-duration GRBs associated with supernovae (SNe; see, e.g., Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003). The different nature of the progenitors is further corroborated by the dichotomy between the hosts of short- and long-duration GRBs: while all morphological types of galaxies can harbour a short-duration GRB (Berger 2009, 2014; Fong et al. 2013), in agreement with the fact that binaries are expected to be widespread, long-duration GRBs are found predominantly in highly star-forming regions (Berger 2014; Klose et al. 2019, and references therein), as expected from a parent population of young massive stars.

Studying GRB host galaxies is therefore crucial for directly investigating the nature of the progenitor, its formation channel, and the circumburst medium. In particular, radio and submillimeter observations can be useful for determining the level of obscured star formation and the overall properties of highly star-forming galaxies at high redshifts, such as metallicity and star formation rate (SFR; Berger et al. 2001), or the interaction between the host galaxy and the surrounding intergalactic medium (Stanway et al. 2015; Michalowski et al. 2015). The first study of the radio properties of GRB host galaxies was performed by Berger et al. (2003): the authors studied 20 sources and found that the SFR inferred from the radio measurements exceeds the values determined from the optical by an order of magnitude, suggesting significant dust obscuration. Conversely, Stanway et al. (2010) observed a sample of five galaxies and found a radio-derived SFR \( < 15 \text{ M}_\odot \text{ yr}^{-1} \), in agreement with the values inferred from optical estimators, suggesting little dust obscuration. Other studies tackled this problem (Berger et al. 2001, 2003; Michalowski et al. 2012, 2015; Hatsukade et al. 2012; Perley & Perley 2013;
Stanway et al. 2014, 2015; Perley et al. 2015; Greiner et al. 2016) and, although they generally agree with the hypothesis of little dust obscuration, a conclusive result is still missing due to the dearth of detected sources: among the approximately 87 host galaxies that have been observed in the radio, only 20 have a confirmed detection, corresponding to a ~23% detection rate. As a consequence, outstanding questions remain unanswered, such as whether or not long GRBs are unbiased tracers of the cosmic star formation history, or whether or not they provide clues as to a particular formation channel of young massive stars (Berger et al. 2001; Ghirlanda & Salvaterra 2022).

A complementary approach is based on the use of ongoing radio sky surveys provided by the Square Kilometre Array (SKA) precursors and pathfinders, such as the Rapid Australian SKA Pathfinder Continuum Survey (RACS; McConnell et al. 2020), the Very Large Array Sky Survey (VLASS; Lacy et al. 2020), and the LOw-Frequency ARray (LOFAR), Two-metre Sky Survey (LoTSS; Shimwell et al. 2017). The rms noise levels of these surveys are seldom deep enough to reveal faint radio emission from GRB hosts; however, they provide a handy resource with which to carry out a systematic search, which is ideal for singling out the most extreme objects for subsequent follow up with dedicated observations. In this paper, we follow this approach and present a detailed radio study of the candidate host galaxy of GRB 200716C based on public survey data and new, dedicated, deep and high angular resolution radio observations.

GRB 200716C triggered the Fermi Gamma-ray Burst Monitor (GBM) at 22:57:41 UT on 2020 July 16, which classified it as a long-duration GRB (Fermi GBM Team 2020; Veres et al. 2021). The prompt emission was subsequently detected by Swift Burst Alert Telescope (BAT) and X-Ray Telescope (XRT; Ukwaatta et al. 2020), AGILE Mini-CALorimeter (Ursi et al. 2020), CALET Gamma-ray Burst Monitor (Torii et al. 2020), Insight-HXMT/HE (Xue et al. 2020), and Konus/Wind (Frederiks et al. 2020), D’Avanzo & CIBO Collaboration (2020) detected an extended source in the Sloan Digital Sky Survey (SDSS) within ~1 arcsec from the location of the optical afterglow of GRB 200716C, and they estimated a photometric redshift of $z = 0.348 \pm 0.053$ for SDSS J130402.36+293840.6 (J1304+2938 hereafter). Other optical detections of this galaxy were subsequently reported (Kumar et al. 2020; Pozanenko et al. 2020; Kann et al. 2020). On the other hand, based on the analysis of its prompt emission light curve, it was recently proposed that GRB 200716C might not be a long-duration GRB, but a short-duration GRB that is lensed by an intermediate-mass black hole (IMBH; $M_{\text{IMBH}} \sim 10^6 M_{\odot}$; Wang et al. 2021; Yang et al. 2021). According to this scenario, the optical source J1304+2938 could be a foreground galaxy hosting the IMBH that gravitationally deforms the emission from GRB 200716C (hence, a background source).

The structure of the paper is the following. The observations and their analysis are reported in Sect. 2. We present and discuss our results in Sects. 3 and 4, respectively. In Sect. 5 we conclude with a brief summary. Throughout the paper we assume a standard Λ-CDM cosmology with $H_0 = 69.32\, \text{km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.286$ and $\Omega_{\Lambda} = 0.714$ (Hinshaw et al. 2013). At $z = 0.341$ (Sect. 3), 1 arcsec corresponds to roughly 4.9 kpc.

2. Observations

2.1. Multi-wavelength archival data

We searched for J1304+2938 in publicly available data and surveys. Its coordinates are (J2000) $\alpha = 13^h 04^m 02.37^s$, $\delta = +29^\circ 38' 40.66''$ (Adelman-McCarthy et al. 2008). This galaxy is present in catalogues produced with LOFAR at 130–170 MHz (LOFAR J1304-29.62+29.389.8, Hardcastle et al. 2016), the Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010) at 3.4, 4.6, 12, and 22 μm (WISE J1304-29.3839.3) and the SDSS (Adelman-McCarthy et al. 2008) in the optical $\pi$, $i$, $r$, $g$, and $u$ filters (SDSS J1304-29.38+29.3840.6, D’Avanzo & CIBO Collaboration 2020). For these three surveys, we obtained the flux densities directly from the above references.

We also investigated the RACS at 0.89 GHz, the Faint Images of the Radio Sky at Twenty-centimeters (FIRST; Becker et al. 1995), the NRAO Very Large Array Sky Survey (NVSS, Condon et al. 1998), and the APERture Tile In Focus array (Apertif, Adams et al. 2022) imaging survey at 1.4 GHz, and the VLASS at 3 GHz. The angular resolution and the epoch of each observation are provided in Table A.1. At the radio wavelengths, the public observations with the highest angular resolution are those from the VLASS, with the beam size being 2.5″. We downloaded the FITS images from The Canadian Initiative for Radio Astronomy Data Analysis (CIRADA) for the NRAO surveys, from the CSIRO ASKAP Science Data Archive (CASDA) for the RACS, and from the Apertif DR1 documentation website for the Apertif imaging survey, and we subsequently performed Gaussian fits with the JMFIT task in the Astronomical Image Processing System (AIPS; Greisen 2003). We show the radio measurements in Fig. 1, while a full spectrum from 0.1 to 10 GHz is provided in Fig. A.1.

2.2. European VLBI Network and e-MERLIN follow up

We also carried out dedicated very long baseline interferometry (VLBI) observations of J1304+2938. On 2021 October 23, we observed at 5 GHz with the European VLBI Network (EVN) for a total time of 6 h (PI: Giarratana; project: J118A). These data were recorded at 2048 Mb/s, and correlated at the Joint Institute for VLBI in Europe (JIVE) into eight sub-arrays (IBFs) with

1 http://cutouts.cirada.ca
2 https://data.csiro.au/domain/casdaObservation
3 https://www.astron.nl/telescopes/wsrp-apertif/apertif-dri-documentation/
32 MHz bandwidth and 64 channels each, through two polarisations (RR, LL).

On 2021 October 30, we performed a sensitive 12 h observation with the EVN including the enhanced Multi-Element Remotely Linked Interferometer Network (e-MERLIN) at 1.6 GHz (PI: Giarratana; project: EG118B). The data were recorded at 1024 Mbits s\(^{-1}\) and correlated at JIVE into eight sub-bands (IFs) with 16 MHz bandwidth and 32 channels each, through two polarisations (RR, LL). The averaging time for the visibilities was of 2 s.

The structure of the observations followed a typical phase-referencing experiment, with scans of \(~3\) min on the target followed by scans of \(~1.5\) min on two phase reference sources (J1310+3220 and J1300+2830). 3C345 was the fringe finder and bandpass calibrator for both the 1.6 and 5 GHz observations.

The calibration and imaging were performed using AIPS following the standard procedure for EVN phase referenced observations, except that for the global fringe fitting, for which we used both the phase calibrators in the following way. We first derived the solutions for J1300+2830, which we applied to the target and the other calibrators. We then derived the residual solutions using a model of the other calibrator J1310+3220, and applied these final solutions to J1310+3220 and the target.

The time- and bandwidth-limited field of view of these observations was of about \(~5\) arcsec, but the source is well localised in the observations with an angular resolution of 2.5 arcsec. Therefore, we searched for the radio emission of the putative host galaxy in an area of 2.5 arcsec in diameter, which corresponds to \(~12\) kpc at \(z = 0.341\) (see also Sect. 3). We adopted a natural weighting scheme to maximise the sensitivity to detect any potential extended structure. We obtained dirty images with an rms of 8\(\mu\)Jy beam\(^{-1}\) at 1.6 GHz, and 9.6\(\mu\)Jy beam\(^{-1}\) at 5 GHz (see Table 1). At 1.6 GHz, the largest angular scale detectable \(\theta_{\text{LAS}}\) is of about 2 arcsec, which corresponds to roughly 10 kpc at \(z = 0.341\), while at 5 GHz it is \(\theta_{\text{LAS}} \sim 50\) mas, which amounts to 245 pc.

2.3. Spectroscopy from the Telescopio Nazionale Galileo

We performed a dedicated spectroscopic follow up of J1304+2938 with the Device Optimized for LOw RESolution (DOLORES) installed at the Telescopio Nazionale Galileo (TNG), with the aim of confirming its photometric redshift. Based on our TNG spectroscopic observations, we determine a redshift of \(z = 0.341 \pm 0.004\). This value confirms and refines the already known photometric redshift of the galaxy (D’Avanzo & CIBO Collaboration 2020). At \(z = 0.341\), the luminosity distance is 1825 Mpc, which gives a scale of 4.9 kpc arcsec\(^{-1}\).

Inspection of the radio surveys, together with measurements available in the literature, reveals unresolved radio emission at the location of the optical galaxy at a significance of between \(\sim 3\sigma\) and \(\sim 4\sigma\) in all the datasets. The resulting flux densities are reported in Table A.1 and shown in the spectrum of Fig. 1, with error bars reporting the 1\(\sigma\) nominal uncertainties from the fitting procedure.

The source is brightest at the lowest frequency, where the LOFAR flux densities range between 4.0 and 7.7 mJy. The spectrum is rather puzzling in this region, with a flat trend between 130 and 150 MHz and a rise between 150 and 200 MHz (Fig. 1). In the \(\sim 1\) GHz region, the source is somewhat fainter; the most significant detection is achieved thanks to the most sensitive Aperi\(f\)it data (1.38\(\pm\)0.04 mJy); the NVSS data indicate slightly larger values, while the highest resolution FIRST data show a slightly lower value, perhaps suggestive of the presence of some extended emission (see Fig. A.2); however, the S/Ns of the NVSS and the FIRST are lower and the results could be considered overall consistent with Aperi\(f\). At 3 GHz, the VLASS data are the only ones in which the fitting result suggests that the source is resolved, providing a significantly larger value for the integrated flux density than the brightness surface peak. However, J1304+2938 is located exactly on a side lobe of the relatively bright (5\(\sigma\)) VLASS data and consider the values for both components in our analysis. The

\footnote{https://www.evlbi.org/evn-data-reduction-guide}

![Fig. 2. TNG DOLORES observed spectrum of the galaxy J1304+2938. The [OII]λ3727 Å line is marked. At \(\sim 5600\) Å a residual sky line remains after the data reduction. The rest frame wavelengths are shown on the upper x-axis.](image-url)
Claim any contribution from the afterglow, whose flux density

B.2. The VLASS survey

The radio-loud AGN

The radio-to-optical luminosity ratio \( R = F_{\text{radio}}/F_{\text{opt}} \) is a classical tool for characterising the radio loudness of an active galaxy (Kellermann et al. 1989). Considering the nearest available bands to those traditionally used to calculate \( R \), we obtain for J1304+2938 a value of \( R \geq 53 \), which is well into the radio-loud domain. The 1.4 GHz radio luminosity from the Apertif imaging survey is \( (5.1\times10^{23}) \) units of W Hz\(^{-1}\) and the steep spectral index in the radio band would place J1304+2938 in the Fanaroff-Riley I (FRI) class (Fanaroff & Riley 1974). However, the available data do not allow direct confirmation of the expected morphology for an FRI radio galaxy, with a compact core and twin jets ending in diffuse, edge-dimmmed lobes or plumes. The survey data are overall compatible with the presence of some diffuse emission on scales of a few tens of kiloparsecs (kpc), as indicated by the apparently resolved nature of the VLASS image and the increase in total flux density when decreasing the resolution in the 1.4 GHz data (from FIRST, to Apertif, and NVSS). If the total extension of the radio emission were confined within a few kpc, the source could be classified as FR0 (Baldi et al. 2016) or a low-power compact source (LPC, Giroletti et al. 2005), which indeed represent a substantial fraction of the radio-loud population at lower redshift (Baldi et al. 2018).

Having multi-frequency and multi-resolution data is an element of novelty in the study of GRB host galaxies, although it leads to a relatively complex picture. The spectrum in Fig. 1 shows a scattered trend between 1 and 3 GHz: the poor S/N of most detections in the surveys explains most of this scatter, although additional factors at work could be external, such as scintillation; physical, such as a variable AGN; or instrumental, in the case of diffuse regions, due to the different angular resolutions of the surveys. As our VLBI observations do not reveal any compact emitters, we can rule out the scintillation scenario. In the following sections, we discuss the origin of the radio emission in the framework of the other two extreme cases: a radio-loud AGN versus emission from a diffuse star-forming region.

4.2. The extreme star formation

An immediate implication of the non-detection with the EVN is that the radio emission detected by lower angular resolution surveys is consistent with being extended on scales that are
larger than the largest detectable angular scale $\theta_{\text{LAS}}$, which is of 2 arcsec at 1.6 GHz (hence smaller than the angular scales sampled by the VLASS). Moreover, the lack of a compact component disfavours variability as the most viable explanation for the discrepancy between low angular resolution measurements. On the other hand, the trend of increasing total flux density when considering lower resolutions in the survey data at 1.4 GHz corroborates the hypothesis of the presence of diffuse emission on galactic scales. Moreover, considering the FIRST and the Apertif imaging surveys, the beam area is roughly 23 and 309 arcsec$^2$ (Fig. A.2), respectively, while the flux density is (790 ± 100) and (1380 ± 40) $\mu$Jy, respectively. Thus, in the FIRST survey we would have a contribution from the galaxy of (590 ± 108) $\mu$Jy spread over 39 beams, and hence an average of (15 ± 3) $\mu$Jy beam$^{-1}$, which is under its rms noise level. This is a rather simplified approach, assuming uniform brightness distribution over the entire Apertif beam area, but it is generally in agreement with the presence of more intense star formation in the central regions (within the ~25 kpc beam of the FIRST) and lower, yet significant additional regions failing in the 140 kpc×54 kpc beam of Apertif.

We further note the presence of a second emitting component in the FIRST and Apertif imaging surveys (Fig. A.2): this contaminating source is found at a distance of ~40 arcsec, which is 200 kpc at $z = 0.341$, and is therefore likely unrelated to J1304+2938. However, in the NVSS, J1304+2938 and the contaminating source are not well separated, possibly explaining the observed discrepancy in the total flux density between the Apertif imaging survey and the NVSS.

Possible mechanisms for a diffuse radio emission unrelated to nuclear activity are the free-free emission from the ionised gas surrounding a population of bright OB stars, which would lead to a thermal spectrum, and/or the SN contribution from young stars, which is characterised by a steep non-thermal spectrum. As our data are clearly suggestive of a steep spectral index, we can assume the latter to be the predominant emission mechanism in the portion of the spectrum we are interested in. Considering the high luminosity we find, this leads to a high SFR$^5$. As the SFR can be inferred from the radio luminosity with different formulas, from the flux density at 1.4 GHz with the FIRST, the Apertif imaging survey, and the NVSS, we estimate that $SFR = (186±42) M_\odot yr^{-1}$, $(324±61) M_\odot yr^{-1}$, and $(376±117) M_\odot yr^{-1}$, using the conversion from Greiner et al. (2016), respectively. Even taking the more conservative SFR derived from the FIRST, J1304+2938 would be among the ten most-star-forming GRB host galaxies discovered so far.

As the SFR derived from the radio is not affected by dust extinction, by comparing it with the value provided by optical estimators, it is possible to determine the amount of dust within the host galaxy, which is important for characterising the environment that leads to a burst (Berger et al. 2001, 2003). To obtain meaningful constraints on the SFR, Michałowski et al. (2012) used a complete sample of 30 hosts with $z < 1$, including those from The Optically Unbiased Gamma-Ray Burst Host (TOUGH) sample (Hjorth et al. 2012) and sources compiled from the literature. The authors found that at least ~63% of GRB hosts have SFR < 100 $M_\odot yr^{-1}$ and at most ~8% can have SFR > 500 $M_\odot yr^{-1}$. Surprisingly, ≥88% of the $z \leq 1$ GRB hosts have UV dust attenuation $A_UV < 6.7$ mag and $A_V < 3$ mag, suggesting that the majority of GRB host galaxies are not heavily obscured by dust. The latter result is further strengthened by subsequent studies on samples of GRB hosts (see e.g., Hatsukade et al. 2012; Perley & Perley 2013; Stanway et al. 2014; Greiner et al. 2016). To determine the level of dust obscuration, a reliable estimate of the SFR from optical estimators is needed, such as the H$\alpha$, H$\beta$, or NII emission lines, which could also provide further confirmation of the photometric redshift. Nevertheless, such optical tests (e.g., Hatsukade et al. 2012) would allow a detailed study of the chemical composition of the galaxy. Among these, the H$\beta$ emission line falls in the wavelength range covered; nevertheless, our spectral observation does not allow us to calculate the SFR from the latter emission lines, possibly due to the fact that they are too weak. A preliminary estimate of the flux expected from the H$\beta$ emission line can be provided by taking the relation between OII, H$\alpha$, and H$\beta$ from Argence & Lamareille (2009), and assuming the ratio OII/H$\alpha = 1.26$ for star-forming galaxies in the local Universe provided by Mouchine et al. (2005); for a S/N of 10.5 for the OII detection, we get a flux three times smaller for the H$\beta$ emission line, which would be too weak to be detected above the continuum emission. Further, deeper spectroscopic follow up is therefore needed.

4.3. J1304+2938 and GRB 200716C

The overall radio properties of J1304+2938 seem to favour a highly star-forming galaxy, which is the natural environment expected for explosive transient events generated during the collapse of young massive stars, such as long-duration GRBs. Therefore, the radio properties of J1304+2938 are in agreement with the long-duration nature of GRB 200716C. Nevertheless, there are still some caveats that are relevant to the interpretation of this burst. First of all, the spectrum of the galaxy in the radio band shows some peculiarities that could be due to the low S/N, the different angular resolutions, and/or the epochs of the surveys. To solve the conundrum, deep observations with arcsecond resolution and a broad bandwidth are required, such those provided by the Karl G. Jansky Very Large Array, for example. Second, considering the isotropic equivalent energy $E_{\text{iso}}$ and the time-integrated peak energy $E_p$ for 150 long- and short-duration Konus/Wind GRBs (Tsvetkova et al. 2017), with $E_{\text{iso}} = 3.7 \times 10^{51}$ erg and $E_p = 880$ keV, GRB 200716C is a clear outlier of the Amati relation, where $E_p = E_{\gamma}(1+z)$, (see Fig. 3 and $E_{\text{iso}}$ was rescaled to $z = 0.341$. This holds true even in the case where J1304+2938 is a foreground galaxy and GRB 200716C is at a higher redshift (Fig. 3, orange dotted line). To be consistent with the 3 $\sigma$ uncertainty of the Amati relation, the uncertainty on the peak energy should be at least ~230 keV (1 $\sigma$). Finally, we note that GRB 200716C is located close to another well-known and still puzzling outlier of the $E_p - E_{\gamma}$ relation, namely GRB 061021 (Nava et al. 2012). Nevertheless, the GRB 061021 host galaxy was not detected up to 6 $\mu$Jy beam$^{-1}$ at 6 GHz (Eftekhari et al. 2021), suggesting different properties with respect to J1304+2938.

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5 we consider a galaxy as highly star forming if SFR $\geq 15 M_\odot yr^{-1}$ (Greiner et al. 2016).

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Table 1. VLBI observations of J1304+2938.

| Array       | Central frequency (GHz) | $T - T_0$ (days) | Angular resolution (arcsec) | Flux density ($\mu$Jy) |
|-------------|-------------------------|------------------|-----------------------------|------------------------|
| EVN+MERLIN  | 1.6                     | 370              | 0.010                       | <24                    |
| EVN         | 5.0                     | 372              | 0.005                       | <29                    |

Notes. Column 1: array; Col. 2: observing frequency (GHz); Col. 3: $T - T_0$ (days), which is the total time from the burst; Col. 4: angular resolution (arcsec); Col. 5: upper limits (3$\sigma$) for the flux density ($\mu$Jy).
The position of GRB 200716C on the $E_{\text{iso}} \sim E_{p,z}$ plane, together with the fact that its prompt emission light curve shows two prominent peaks, followed by an extended emission up to $T_{90} \sim 90$ s (Veres et al. 2021; Barthelmy et al. 2020; Torii et al. 2020; Xue et al. 2020), led some authors to question the long-duration nature of this burst. An alternative explanation could be that GRB 200716C is a short-duration GRB gravitationally lensed by an IMBH, which is probably hosted by J1304+2938 (Wang et al. 2021; Yang et al. 2021). We highlight the fact that, because of their high luminosities (up to $10^{53-54}$ erg s$^{-1}$; Piran 2004; Kumar & Zhang 2015), GRBs can be detected up to the highest redshifts (the farthest GRB currently known is GRB 090429B at a photometric redshift of $z = 9.4$; Cucchiara et al. 2011) and therefore they can be used as probes of the early Universe (Fryer et al. 2022). As they could be cosmologically distant events, some GRBs might be gravitationally lensed (e.g., Paynter et al. 2021 and references therein). Because of the strong lensing effect, photons coming from a distant source travel different geometric paths as they approach the foreground lensing object and form multiple magnified images of the same background source (Congdon & Keeton 2018). As a consequence, we observe variations in the lensed images with a time delay that depends on the gravitational potential of the lens. In the case of GRBs, if gravitationally lensed, we expect to measure a bright $\gamma$-ray pulse followed by a dimmer duplicate. To date only a few GRBs have been suggested as candidate lensed events, namely GRB 950830 (Paynter et al. 2021), GRB 210812A (Veres et al. 2020), GRB 081126A, and GRB 090717A (Lin et al. 2022), based on the analysis of their light curves.

If J1304+2938 hosts the gravitational lens of GRB 200716C, VLBI observations could potentially detect a compact emission from a radio-loud IMBH acting as a (milli-)lens (e.g., Paragi et al. 2006). Possible radio emission from an IMBH would greatly help our understanding of the localisation of these objects in galaxies, which is highly unconstrained from an observational perspective (e.g., Weller et al. 2022). Ultra-luminous X-ray sources (ULXs) have been suggested as possible IMBHs (Kaaret et al. 2001; Miller et al. 2003) and they are variable objects on different timescales (from months to years; see e.g., Lasota et al. 2011; Earnshaw et al. 2016; Atapin et al. 2019). However, not even our sensitive VLBI follow up can shed light on this hypothesis as the radio emission from accreting IMBH can only be detected in local galaxies (Cseh et al. 2015; Mezcua et al. 2018).

To date, only a few (macro-)lensing galaxies showing radio/mm emission (McKean et al. 2007; Haas et al. 2014; Paraficz et al. 2018) have been found, making ‘radio-emitting’ lenses extremely rare objects. In general, VLBI is the only method that allows us to pinpoint the multiple images produced by a gravitational lens with mass $<10^{5-6} M_\odot$, which are expected to be separated by a few mas (Siringola et al. 2019; Casadio et al. 2021). Nevertheless, in order to detect the putative radio-lensed images of GRB 200716C, the VLBI observations would have had to be carried out within a few hours or days of the detection of the burst at $\gamma$-rays.

5. Conclusions

In this paper, we present the analysis of dedicated VLBI observations together with IR and optical public data of the putative host galaxy J1304+2938 of GRB 200716C at $z = 0.341$. We set stringent upper limits (sensitivity of $<10^{-3}$ Jy beam$^{-1}$) on the presence of compact radio emission, namely $<50$ mJy at 5 GHz, within a field of view of 2.5 arcsec at 1.6 and 5 GHz. Moreover, by performing a dedicated spectroscopic follow up with the TNG, we corroborate the previous redshift estimate of the galaxy (D’Avanzo & CIBO Collaboration 2020).

The non-detection with EVN and EVN+e-MERLIN suggests that the radio emission detected at low angular resolution by the RACS, FIRST, the Apertif imaging survey, and the NVSS and VLASS surveys might be diffuse and therefore completely resolved out by our VLBI observations. Moreover, the observed scatter in the publicly available flux density measurements at low frequencies cannot be explained by a variable, compact source, further corroborating the hypothesis of diffuse emission from highly star-forming regions. We derive a 1.4 GHz luminosity of greater than $10^{30}$ erg s$^{-1}$ Hz$^{-1}$, which implies a SFR $\sim 300 M_\odot$ yr$^{-1}$. This high SFR is consistent with the most extreme environments for long-duration GRBs. That being the case, J1304+2938 would be among the most radio-bright long-GRB host galaxies discovered so far. Nevertheless, the temporal and spectral properties of the prompt emission of GRB 200716C, together with the offset with respect to the Amati relation for long-duration GRBs, mean that the nature of this burst remains puzzling.

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6 These radio-loud lenses are at higher redshifts than J1304+2938 ($z \sim 0.65-0.8$).
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use of data from the Apertif system installed at the Westerbork Synthesis Radio

University of Colorado Boulder, University of Oxford, University of Portsmouth,

University, Shanghai Astronomical Observatory, United Kingdom Participation/

New Mexico State University, New York University, University of Notre Dame,

Extraterrestrische Physik (MPE), National Astronomical Observatories of China,

Canarias, The Johns Hopkins University, Kavli Institute for the Physics and

Participation Group, the French Participation Group, Instituto de Astrofísica de

Mellon University, Center for Astrophysics, Harvard & Smithsonian, the Chilean

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Appendix A: Photometric data

Table A.1 presents the various measurements for J1304+2938 available from the literature and/or our analysis of survey data. Figure A.1 presents the flux density measurements (mJy) as a function of frequency (GHz), from 0.1 to 10^6 GHz. Figure A.2 shows the radio detection of J1304+2938 in the FIRST surveys, in white). Appendix A: Photometric data

Table A.1. Publicly available data for J1304+2938 from different surveys.

| Survey / Instrument | Central frequency (GHz) | Date            | Angular resolution (arcsec) | Flux density (mJy) | Ref.                  |
|---------------------|-------------------------|-----------------|------------------------------|--------------------|-----------------------|
| LOFAR               | 0.130                   | <15/07/2014     | 6×10                         | 4.1±0.7            | Hardcastle et al. (2016) |
| LOFAR               | 0.138                   | <15/07/2014     | 6×10                         | 4.2±0.7            | Hardcastle et al. (2016) |
| LOFAR               | 0.146                   | <15/07/2014     | 6×10                         | 4.1±0.7            | Hardcastle et al. (2016) |
| LOFAR               | 0.150                   | <15/07/2014     | 6×10                         | 5.2±0.4            | Hardcastle et al. (2016) |
| LOFAR               | 0.154                   | <15/07/2014     | 6×10                         | 4.0±0.7            | Hardcastle et al. (2016) |
| LOFAR               | 0.161                   | <15/07/2014     | 6×10                         | 7.4±1.0            | Hardcastle et al. (2016) |
| LOFAR               | 0.169                   | <15/07/2014     | 6×10                         | 7.7±1.3            | Hardcastle et al. (2016) |
| RACS                | 0.89                    | 21/04/2019      | 26×11                        | 1.3±0.2            | This work             |
| FIRST               | 1.4                     | 02/04/1993      | 5.4                          | 0.79±0.10          | This work             |
| Apertif imaging survey | 1.4                   | 15/11/2019      | 28.6×11.1                    | 1.38±0.04          | This work             |
| NVSS                | 1.4                     | 11/01/1994      | 45                           | 1.6±0.4            | This work             |
| Vlass1a             | 3                      | 25/11/2017      | 3.0×2.3                      | 0.38±0.10          | This work             |
| Vlass1b             | 3                      | 25/11/2017      | 3.0×2.3                      | 1.4±0.5            | This work             |
| Vlass2a             | 3                      | 9/10/2020       | 2.7×2.4                      | 0.56±0.12          | This work             |
| Vlass2b             | 3                      | 9/10/2020       | 2.7×2.4                      | 1.3±0.3            | This work             |
| Vlass-combineda     | 3                      | 30×2.3          | 0.47±0.08                    | This work          |
| Vlass-combinedb     | 3                      | 3×2.3           | 1.3±0.3                      | This work          |
| WISE                | 1.36×10^4               | <06/08/2010     | 12                           | < 1.6              | Wright et al. (2010)  |
| WISE                | 1.36×10^4               | <06/08/2010     | 12                           | < 3.7              | Wright et al. (2010)  |
| WISE                | 1.36×10^4               | <06/08/2010     | 12                           | < 4.6              | Wright et al. (2010)  |
| WISE                | 2.59×10^4               | <06/08/2010     | 6.5                          | < 0.5              | Wright et al. (2010)  |
| WISE                | 2.59×10^4               | <06/08/2010     | 6.5                          | < 0.7              | Wright et al. (2010)  |
| WISE                | 2.59×10^4               | <06/08/2010     | 6.5                          | 0.4±0.2            | Wright et al. (2010)  |
| WISE                | 6.51×10^4               | <06/08/2010     | 6.4                          | 0.158±0.011        | Wright et al. (2010)  |
| WISE                | 6.51×10^4               | <06/08/2010     | 6.4                          | 0.19±0.02          | Wright et al. (2010)  |
| WISE                | 6.51×10^4               | <06/08/2010     | 6.4                          | 0.24±0.03          | Wright et al. (2010)  |
| WISE                | 8.94×10^4               | <06/08/2010     | 6.1                          | 0.25±0.008         | Wright et al. (2010)  |
| WISE                | 8.94×10^4               | <06/08/2010     | 6.1                          | 0.309±0.012        | Wright et al. (2010)  |
| WISE                | 8.94×10^4               | <06/08/2010     | 6.1                          | 0.35±0.03          | Wright et al. (2010)  |
| SDSS (z)            | 3.36×10^5               | 23/05/2004      | 0.141±0.012                  | Ahumada et al. (2020) |
| SDSS (i)            | 4.01×10^5               | 23/05/2004      | 0.104±0.003                  | Ahumada et al. (2020) |
| SDSS (r)            | 4.86×10^5               | 23/05/2004      | 0.072±0.002                  | Ahumada et al. (2020) |
| SDSS (g)            | 6.40×10^5               | 23/05/2004      | 0.024±0.001                  | Ahumada et al. (2020) |
| SDSS (u)            | 8.45×10^5               | 23/05/2004      | 0.010±0.003                  | Ahumada et al. (2020) |

Notes. Column 1: survey or instrument. Column 2: observing frequency (GHz). Column 3: Date of the observation. Column 4: angular resolution (arcsec). Column 5: Flux density (mJy). The upper limits for the flux density are given with a 1 σ confidence. Column 6: References. a From JMFIIT peak intensity. b From JMFIIT integral intensity.
Fig. A.1. Flux-density measurements (mJy) as a function of frequency (GHz) for J1304+2938 from 0.1 to $10^6$ GHz. The inset shows the LOFAR data, while the arrows indicate the 3σ upper limits. Data are taken at different epochs (see Table A.1). The dashed red line corresponds to a power law $F \propto \nu^\alpha$ with spectral index $\alpha = -0.75$.

Fig. A.2. Radio detection of J1304+2938 in the FIRST survey at 1.4 GHz, shown by the coloured map and the associated colour bar. The surface brightness contours at levels of 3, 6, 12, 24, and 48σ from the Apertif imaging survey are superimposed in white, where the rms noise level of the Apertif imaging survey is $\sigma = 40 \mu$Jy beam$^{-1}$. On the lower left, the restoring beams are shown as a red and a white ellipse for the FIRST and the Apertif imaging survey, respectively. A second, resolved source at roughly 40 arcsec is found to the south.
Appendix B: Luminosities of the GRB host galaxies

Table B.1 presents the redshift, the radio (monochromatic) luminosity, the frequency, and star-formation rate (SFR) for the GRB host galaxies detected in radio. The SFR was calculated from the observed flux density at a frequency $\nu$, host galaxies detected in radio. The SFR was calculated from the flux density at a frequency $\nu$, according to the following formula (Greiner et al. 2016):

$$\left( \frac{\text{SFR}}{M_{\odot}/\text{yr}} \right) = \frac{F_\nu}{\mu\text{Jy}} \left(1 + z\right)^{-\alpha-1} \left( \frac{D_L}{\text{Gpc}} \right)^2 \left( \frac{\nu}{\text{GHz}} \right)^{-\alpha},$$

(B.1)

where $F_\nu$ is the flux at the frequency $\nu$, $z$ is the redshift, $D_L$ is the luminosity distance, and $\alpha$ is the spectral index, which we assume to be -0.75. In addition to the sources reported in Table B.1, we collected 67 non-detections from the literature, resulting in upper limits on the SFRs down to <0.02 $M_{\odot}$ yr$^{-1}$ (GRB 060218, Greiner et al. 2016).

Table B.1. Long-duration GRB host galaxies detected in radio so far.

| GRB      | z   | $\nu$ (GHz) | $F_\nu$ ($\mu\text{Jy beam}^{-1}$) | $L_\nu$ (erg s$^{-1}$ Hz$^{-1}$) | SFR $M_{\odot}$ yr$^{-1}$ | Ref.              |
|----------|-----|-------------|------------------------------------|-------------------------------|---------------------------|-------------------|
| 980425   | 0.0085 | 1.38        | 840±160                           | (1.4±0.3)$\times$10$^{27}$   | 0.08±0.02                 | Michałowski et al. (2012) |
| 980703   | 0.967  | 1.43        | 76±10                             | (3.2±0.4)$\times$10$^{30}$   | 206±27                    | Berger et al. (2001)  |
| 000418   | 1.119  | 1.43        | 69±15                             | (4.1±0.9)$\times$10$^{30}$   | 264±57                    | Berger et al. (2003)  |
| 020819B  | 0.41   | 3.0         | 31±8                              | (1.7±0.4)$\times$10$^{29}$   | 20.5                      | Greiner et al. (2016) |
| 021211   | 1.006  | 1.43        | 330±31                            | (1.5±0.1)$\times$10$^{31}$   | 982±82                    | Michałowski et al. (2012) |
| 031203  a | 0.105  | 1.39        | 254±46                            | (7±1)$\times$10$^{38}$       | 4.5±0.8                   | Michałowski et al. (2012) |
| 050223   | 0.591  | 5.5         | 90±30                             | (1.2±0.4)$\times$10$^{30}$   | 210±70                    | Stanway et al. (2014)  |
| 051006   | 1.059  | 3.0         | 9±3                               | (5±2)$\times$10$^{29}$       | 53±18                     | Perley et al. (2015)  |
| 051022   | 0.809  | 5.23        | 13±4                              | (4±1)$\times$10$^{29}$       | 61±19                     | Perley & Perley (2013) |
| 060505   | 0.089  | 1.38        | 76±35                             | 1.5±0.7$\times$10$^{28}$     | 0.9±0.4                   | Michałowski et al. (2015) |
| 060729  b | 0.54   | 5.5         | 65±28                             | (7±3)$\times$10$^{29}$       | 123±53                    | Stanway et al. (2014)  |
| 060814   | 1.92   | 3.0         | 11±3                              | (2.3±0.6)$\times$10$^{30}$   | 258±70                    | Perley et al. (2015)  |
| 061121   | 1.314  | 3.0         | 17±5                              | (1.5±0.4)$\times$10$^{30}$   | 165±48                    | Perley et al. (2015)  |
| 070306   | 1.496  | 3.0         | 11±3                              | (1.3±0.4)$\times$10$^{30}$   | 145±39                    | Perley et al. (2015)  |
| 080207   | 2.086  | 5.23        | 17±2                              | (4.3±0.5)$\times$10$^{30}$   | 731±86                    | Perley & Perley (2013) |
| 080517   | 0.089  | 4.5         | 220±40                            | (4.4±0.8)$\times$10$^{28}$   | 7±1                      | Stanway et al. (2015)  |
| 090404  d | 3.0    | 5.23        | 11±3                              | (6±2)$\times$10$^{30}$       | 1074±293                  | Perley & Perley (2013) |
| 100316D  | 0.059  | 1.38        | 657±21                            | (5.5±0.2)$\times$10$^{28}$   | 3.5±0.1                   | Michałowski et al. (2015) |
| 100621A  c | 0.542  | 5.5         | 120±32                            | (1.3±0.3)$\times$10$^{30}$   | 229±61                    | Stanway et al. (2014)  |
| 111005A  | 0.013  | 1.38        | 245±30                            | (9±1)$\times$10$^{26}$       | 0.06±0.01                 | Michałowski et al. (2015) |
| 200716C  | 0.341  | 1.4         | 1380±40                           | (5.1±0.2)$\times$10$^{30}$   | 324±61                    | This work          |

Notes. Column 1: GRB name. Column 2: redshift. Column 3: observing frequency (GHz). Column 4: Flux density ($\mu\text{Jy beam}^{-1}$) referred to the observing frequency. Column 5: monochromatic luminosity (erg s$^{-1}$ Hz$^{-1}$). Column 6: SFR calculated with the formula provided by Greiner et al. (2016). Column 7: References. The uncertainties on the monochromatic luminosity and the SFR are derived with the standard formula for the propagation of errors. a We used the flux density measurement at 1.39 GHz from Michałowski et al. (2012), while the SFR from Greiner et al. (2016) is derived from the flux density at 5.5 GHz. b We used the flux density value from Stanway et al. (2014) at 5.5 GHz, while Greiner et al. (2016) derived an upper limit for the SFR using the upper limit for the flux density at 1.39 GHz from Michałowski et al. (2012). c We used the flux density at from Stanway et al. (2014), while Greiner et al. (2016) used an upper limit for the flux density at 2.1 GHz. d Even though the host galaxy of GRB 090404 was detected by Perley & Perley (2013), the authors stated that an afterglow origin for the observed detection could not be ruled out.