Cosmic evolution of star-forming galaxies to $z \approx 1.8$ in the faint low-frequency radio source population

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ABSTRACT

We study the properties of star-forming galaxies selected at 610 MHz with the GMRT in a survey covering $\sim 1.86 \text{ deg}^2$ down to a noise of $\sim 7.1 \mu$Jy / beam. These were identified by combining multiple classification diagnostics: optical, X-ray, infrared and radio data. Of the 1685 SFGs from the GMRT sample, 496 have spectroscopic redshifts whereas 1189 have photometric redshifts. We find that the IRRC of star-forming galaxies, quantified by the infrared-to-1.4 GHz radio luminosity ratio $q_{\text{IR}}$, decreases with increasing redshift: $q_{\text{IR}} = 2.86 \pm 0.04(1 + z)^{-0.20 \pm 0.02}$ out to $z \approx 1.8$. We use the $V/V_{\text{max}}$ statistic to quantify the evolution of the co-moving space density of the SFG sample. Averaged over luminosity our results indicate $\langle V/V_{\text{max}} \rangle$ to be $0.51 \pm 0.06$, which is consistent with no evolution in overall space density. However we find $V/V_{\text{max}}$ to be a function of radio luminosity, indicating strong luminosity evolution with redshift. We explore the evolution of the SFGs radio luminosity function by separating the source into five redshift bins and comparing to theoretical model predictions. We find a strong redshift trend that can be fitted with a pure luminosity evolution of the form $L_{610\text{MHz}} \propto (1 + z)^{-(3.25 \pm 0.30) - (5.02 \pm 0.15)}$. We calculate the cosmic SFR density since $z \sim 1.5$ by integrating the parametric fits of the evolved 610 MHz luminosity function. Our sample reproduces the expected steep decline in the star formation rate density since $z \sim 1$.

Key words: galaxies: luminosity function, galaxies: starburst, large-scale structure of Universe, radio continuum: galaxies

1 INTRODUCTION

Radio continuum observations provide dust unbiased information on mechanical feedback originating in star formation and AGN radio jets (Condon 1992; Merloni & Heinz 2007; Madau & Dickinson 2014). They thus underpin our understanding of galaxy evolution over cosmic time. Multi-wavelength analysis of the GMRT 610 MHz deep ELAIS-N1 data down to flux densities of $50 \mu$Jy by Ocran et al. (2017) clearly shows the transition from an AGN dominated population to a star-forming galaxy (SFG) below flux densities of $\sim 300 \mu$Jy. This is in line with what found in 1.4 GHz deep surveys. This flux depends on the frequency. (Condon 1989; Mauch & Sadler 2007; Padovani et al. 2015; Prandoni et al. 2018).

The synchrotron emission in SFGs is closely related to recent star formation, so that its emission is widely used as a star formation indicator. This is due to the short lifetime of the massive stars producing Type II and Type Ib supernovae (e.g. see Condon 1992; Bell 2003; Murphy et al. 2011a). The total infrared luminosity of a galaxy and its total 1.4 GHz radio luminosity are known to be linearly and tightly correlated (e.g. see van der Kruit 1971; de Jong et al. 1985; Helou et al. 1985; Condon 1992; Bell 2003; Sargent et al. 2010). This so called infrared-radio correlation (IRRC) is well established for SFGs (e.g. Ivison et al. 2010; Magnelli et al. 2010; Thomson et al. 2014).

The evolution of different radio populations conducted
by using non-parametric \( V/V_{\text{max}} \) analysis (Schmidt 1968; Morris et al. 1991; Yun et al. 2001). Clewley & Jarvis (2004) used the \( V/V_{\text{max}} \) test to show that low luminosity radio sources evolve differently from their more powerful, predominantly Fanaroff-Riley type II (FRII). McAlpine & Jarvis (2011) used \( V/V_{\text{max}} \) test to investigate the cosmic evolution of low luminosity (1 GHz < 10^25 W Hz^{-1} sr^{-1}) radio sources in the XMM Large Scale Structure survey field (XMM-LSS). Their results indicate that the low luminosity sources evolve differently to their high luminosity counterparts out to a redshift of \( z \approx 0.8 \).

The bivariate luminosity function of an optical-radio matches sample describes the volume density of galaxies per unit interval of radio luminosity per interval of optical luminosity in each redshift bin. The evolution of star-forming galaxies has been extensively studied over the years using optical and infrared surveys. Mid and far-infrared Spitzer observations indicate that the galaxy population undergoes pure luminosity evolution with \( k \sim 3.4 \)–3.8 out to \( z \sim 1.2 \), where \( k \) is the pure density evolution (PDE) (e.g. Caputi et al. 2007; Magnelli et al. 2009; Rutnapakarn et al. 2010; Magnelli et al. 2011). While far infrared luminosity functions from Herschel data result in slightly stronger evolution estimates with \( L_{\star} \propto (1 + z)^{2.1 \pm 0.3} \) up to \( z \sim 1.5 \) (Gruppioni et al. 2010; Lapi et al. 2011). At low redshifts (\( z < 0.5 \)) Herschel studies performed by Dye et al. (2010) suggested evidence of stronger evolution in star-forming galaxies with the total luminosity density evolving as \( (1 + z)^{7.1} \).

At radio wavelengths there has been substantial work on AGN but SFGs only become significant at low flux densities, hence are becoming more accessible with deep surveys. Mauch & Sadler (2007) studied a sample of 7824 radio sources from 1.4 GHz NRAO Very Large Array (VLA) Sky Survey (NVSS) with galaxies brighter than \( K = 12.75\text{mag} \) in the Second Incremental Data Release of 6dF Galaxy Survey (6dFGS-DR2) that spanned a redshift range \( 0.003 < z < 0.3 \) and determined the local luminosity function at 1.4 GHz for their 60% star forming galaxies (SFGs) and 40% active galactic nuclei (AGN). Smolčić et al. (2009a) derived the cosmic star formation history (CSFH) out to \( z = 1.3 \) using a sample of \( \sim 350 \) radio selected star forming galaxies and determined an evolution in the 1.4 GHz luminosity function based on the VLA-COSMOS SFGs. Mao et al. (2012) used the Data Release 1 (DR1) from the Australia Telescope Large Area Survey (ATLAS) consisting of the preliminary data published by Norris et al. (2006) and Middelberg et al. (2008) et al. (2008) and reaching an rms sensitivity of \( 30 \mu Jy\text{beam}^{-1} \) to derive radio luminosity functions. They constructed the radio luminosity function for star-forming galaxies to \( z = 0.5 \) and for AGN to \( z = 0.8 \) and found that radio luminosity function for star-forming galaxies appears to be in good agreement with previous studies. McAlpine et al. (2013) investigated the evolution of faint radio sources out to \( z \sim 2.5 \) by combining a 1 square degree VLA radio survey complete to a depth of \( 100\mu Jy \) with the following surveys: Visible and Infrared Survey Telescope for Astronomy Deep Extragalactic Observations and Canadian-France-Hawaii Telescope Legacy Survey. Novak et al. (2017) use of the deep Karl G. Jansky Very Large Array (VLA) COSMOS radio observations at 3 GHz to infer radio luminosity functions of star-forming galaxies up to redshift of \( z \approx 5 \) based on 6040 detections with reliable optical counterparts.

In the low-frequency regime, Willott et al. (2001) measure the radio luminosity function (RLF) of steep-spectrum radio sources using three redshift surveys of flux-limited samples selected at low (151 and 178 MHz) radio frequency, low-frequency source counts and the local RLF. Prescott et al. (2016) presented a measurement of the evolution of SFGs to \( z = 0.5 \), by matching a catalogue of radio sources measured at a frequency of 325 MHz from the Giant Metrewave Radio Telescope (GMRT) to their optical counterparts in the Galaxy And Mass Assembly (GAMA) survey. They found that the radio luminosity function at 325 MHz for SFGs closely follows that measured at 1.4 GHz.

The evolution of the global galaxy SFR density can be used as a robust constraint on various simulations and semi-analytic models of galaxy evolution (e.g., Pei et al. 1999; Somerville et al. 2001; McCarthy et al. 2001). Total CSFH has been constrained using MIR (24/8\( \mu m \)) selected samples obtained by deep small area surveys (Zheng et al. 2006; Caputi et al. 2007; Bell et al. 2007). Smolčić et al. (2009a) used the VLA-COSMOS SFGs to derive the cosmic star formation history out to \( z = 1.3 \). In this paper, we present a measurement of the evolution of SF galaxies to \( z 

1 http://www.mattiavaccari.net/df
before mosaic, for each pointing were in the range 4.5 to 6 arcseconds. The minimum rms noise in the central region of the image is 7.1 $\mu$Jy beam$^{-1}$. The radio data is fully described in Ocran et al. (2019). Data analysis was carried out on the data intensive cloud at the Inter-University Institute for Data Intensive Astronomy (IDIA). A source catalogue was produced by extracting sources in the mosaic using the PyBDSF source finder (Mohan & Rafferty 2015). This resulted in a final catalogue of 4290 radio sources. By matching to multi-wavelength data against SERVS IRAC12 positions Fusion$^2$ (Vaccari et al. 2010; Vaccari 2015), we obtain a redshift estimate for 72%, with 19% based on spectroscopy. The redshift estimates are a combination of spectroscopic and photometric redshifts from (i.e. the Hyper Suprime-Cam (HSC) Photometric Redshift Catalogue (Tanaka et al. 2018), the revised SWIRE Photometric Redshift Catalogue (Rowan-Robinson et al. 2013) and the Herschel Extragalactic Legacy Project (Vaccari 2016; Shirley et al. 2019, HELP) ). For 3105 of the sources with redshifts we use radio and X-ray luminosity, optical line ratios, mid-infrared colors, and 24$\mu$m and IR to radio flux ratios to separate SFGs from AGN. In Ocran et al. (2019), we outlined that total number of sources with redshifts for which we can define at least one AGN indicator was 2305 (i.e. $\sim$54% of the whole 4290 sample and $\sim$74% of the 3105 sources with redshifts). We classified 1685 sources as SFG constituting 73% of the 2305 sources for which we were able to define at least one AGN indicator for source classification. For sources with redshift, rest frame 610 MHz radio luminosities are calculated using equation 1 below:

$$L_{610} = 4\pi D_L^2 \frac{S_{\text{obs}}}{(1+z)^{1+\alpha}} \tag{1}$$

where $L$ is the luminosity in WHz$^{-1}$ at the frequency $\nu$, $D_L$ is the luminosity distance in metres. $S_{\text{obs}}$ is the observed flux density at 610 MHz, and $\alpha$ is the spectral index and it is defined as $S \propto \nu^{\alpha}$. In Ocran et al. (2019), we measured a median spectral index that steepens with frequency with $\alpha_{610}^{325} = -0.80 \pm 0.29$, for $\sim$479 sources and $\alpha_{1400} = -0.83 \pm 0.31$ for $\sim$99 sources. Hence, we use the canonical spectral index of $\alpha = -0.8$ often assumed for SFGs (Condon 1992).

### 2.1 The SFG sample

From Ocran et al. (2019), we have a multi-wavelength match for 92% of the sources and a redshift identification for 72% of the sources. But we have been able to classify 39% as SFGs and 15% as AGNs which adds up to 54%. If there is an indication of AGN activity in the source from any of the criteria adopted, then we inferred that the source is an AGN, regardless of the results from the other indicators. Thus, the sources classified as SFGs are those sources in our redshift sample that do not show evidence of AGN activity in any of the diagnostics. This may be considered as an upper limit to

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the population of sources in this flux density regime whose radio emission is powered by star formation processes.

Figure 2 shows the distribution of 610-MHz flux densities. The entire GMRT sample of 4290 sources (i.e. light gray histogram) is represented as $S_{\text{ALL}}$. Radio sources that have multi-wavelength identification (i.e black histogram) is represented as $S_{\text{matched}}$. Whereas radio sources with redshifts (i.e. red histogram) is represented as $S_z$. The sources with redshifts that also have at least one diagnostic for AGN activity (i.e. red histogram) is represented as $S_{\text{AGN diagnostic}}$. The SFG sample used for this analysis is drawn from the latter. We use these distributions to derive the redshift success $C_z$ completeness which is outlined in subsection 4.2.

### 3 SFG PROPERTIES

Figure 1 shows the distribution of the GMRT sources (grey histogram) with $m_{\text{mag}}$ (left) and redshift (right). We overplot the distribution of objects identified as SFG in black. The redshift distribution clearly shows that the sample is incomplete for $m_{\text{mag}} > 25$ and $z > 1.5$. This is driven by HSC/Subaru photometric redshifts, which start being incomplete at $z \sim 1.3$. Tanaka et al. (2018) stresses that photometric redshifts should only be used at $z \lesssim 1.5$ and $l \lesssim 25$.

We note a secondary peak in our sample at $z \sim 1.1$ and $r \sim 25$. Swinbank et al. (2007) identified five candidate galaxy overdensities at $z \sim 1$ across $\sim 1$ deg$^2$ in the EN1 field by analysing deep field of the UK Infrared Deep Sky Survey (UKIDSS) Deep eXtragalactic Survey. They attributed these five overdense regions lying in a narrow redshift range as an indication of the presence of a supercluster in this field at $z \sim 1$. Our secondary peak may be due to this supercluster.

#### 3.1 The redshift evolution of the IRRC

We characterised the IR/radio correlation of our SFGs by the logarithmic ratio between the IR bolometric ($8\text{-}1000\mu\text{m}$) luminosity and the radio luminosity $q_{\text{IR}}$ (Helou et al. 1985).

$$q_{\text{IR}} = \log_{10} \left( \frac{L_{\text{IR}}}{3.75 \times 10^{12} \text{W}} \right) - \log_{10} \left( \frac{L_{\text{radio}}}{\text{W Hz}^{-1}} \right)$$

where $L_{\text{IR}}$ is the total rest-frame infrared luminosity and $L_{\text{radio}}$ is the luminosity at the radio frequency to be studied, in our case at 610 MHz and 1.4 GHz in W/Hz. The 1.4 GHz luminosities were computed from the $S_{610\text{MHz}}$ using a radio spectral index of $-0.8$. The far-Infrared luminosities, $L_{\text{fIR}}$, were derived from rest-frame integrated $8\text{-}1000\mu\text{m}$ luminosities, estimated by Malek et al. (2018) using HELP photometry. They were obtained by performing SED fitting on the ultraviolet(UV)/near-infrared(NIR) to far-infrared(FIR) emission of 42,047 galaxies from the pilot HELP field: EN1. We corrected the luminosity values to our more accurate spectroscopic redshift by following the prescription presented by Ocran et al. (2017).

We investigate the evolution of the $q_{\text{IR}}$ parameter with redshift which is quantified by the function $q_{\text{IR}} \propto (1 + z)^\gamma$ (Ivison et al. 2010; Calistro Rivera et al. 2017). We first analyse the 1.4 GHz behavior because this can be compared to the literature. Figure 3 shows $q_{\text{IR}}$ vs redshift. The inset histogram shows $q_{\text{IR}}$ is scattered in a distribution with an overall median value of $q_{\text{IR}} = 2.61^{+0.30}_{-0.28}$ (see the red horizontal solid line in Figure 3). This $q_{\text{IR}}$ distribution agrees well with previous literature within the errors. Yun et al. (2001) measured a median $q_{\text{IR}} = 2.34 \pm 0.26$ (see the dashed horizontal line in Figure 3), by investigating the radio counterparts to the IRAS redshift survey galaxies that are also identified in the NRAO VLA Sky Survey (NVSS) catalog. The horizontal shaded region represents the $\pm 0.26$ upper and lower bounds around the median value. Bell (2003) assembled a diverse sample of galaxies from the literature with far-ultraviolet (FUV), optical, infrared (IR), and radio luminosities to explore the origin of the radio-IR correlation and measured a median $q_{\text{IR}} = 2.64 \pm 0.02$ (see the dotted dashed horizontal line in Figure 3). We note that Bell (2003) used total infrared (TIR) luminosities, but Yun et al. (2001) value is based on far-infrared (FIR) luminosities. Delhaize et al. (2017) showed that this usually results in lower median values. We split the data into seven redshift bins, Table 1 presents the number of sources, median value of $z$ and $q_{\text{IR}}$ for star-forming galaxies in each redshift bin. By fitting a power-law function to the median values of $q_{\text{IR}}$, weighting by the uncertainty, we find a significant variation of $q_{\text{IR}}$ with redshift: $q_{\text{IR}} = 2.86 \pm 0.04(1 + z)^{-0.20\pm0.02}$. The errors here are the 1σ uncertainty from the power-law fit. Our result is in good agreement with Delhaize et al. (2017), who carried out double-censored survival analysis (following Sargent et al. (2010)) to calculate the median $q_{\text{IR}}$ values (and associated 95% confidence intervals) for their samples in redshift bins. To get $q_{\text{IR}}$ they converted their 3 GHz luminosities to 1.4 GHz ones using a spectral index of 0.7. They reported a slightly higher but statistically significant variation of $q_{\text{IR}}$ with redshift: $q_{\text{IR}} = 2.88 \pm 0.03(1 + z)^{-0.19\pm0.01}$ from a highly sensitive 3 GHz observations with the Karl G. Jansky Very Large Array (VLA) and infrared data from the Herschel Space Observatory in the 2 deg$^2$ COSMOS field. Despite the fact that we do not follow the survival analysis approach (see Schmitt et al. 1993; Novak et al. 2017; Ceraj et al. 2018; Mohlár et al. 2018), we nevertheless get results in good agreement, implying that our analysis is not significantly biased.

Magnelli et al. (2015) found a moderate but statistically significant redshift evolution $q_{\text{IR}}(z) = 2.35 \pm 0.08(1 + z)^{-0.12 \pm 0.04}$ using deep FIR luminosities from the Herschel Space Observatory (Pilbratt et al. 2010) and deep radio 1.4 GHz VLA observations. Calistro Rivera et al. (2017) measured the redshift evolution of the infrared-radio correlation (IRC) for SFG sample obtained with Low Frequency Array (LOFAR) at 150 MHz and found that the ratio of total infrared to 1.4 GHz data of the Booites field decreases with increasing redshift given by: $q_{\text{IR}} = 2.45 \pm 0.04(1 + z)^{-0.15\pm0.03}$.
4 RADIO LUMINOSITY FUNCTION

4.1 Sample selection

To study the evolution of the Radio Luminosity Function (RLF) we limit our sample to SFGs with \( r_{\text{mag}} \text{lim} = 25 \) and

\[ 0.002 < z < 1.5, \] making 1291 SFGs in total. We choose \( r_{\text{mag}} \text{lim} = 25 \) to maximise the number of sources that we can use to calculate the luminosity function. Table 2 presents a summary of the number and percentage of all the SFGs with spectroscopic and photometric redshifts (a). The number and percentage of the SFGs that satisfies the selection for computing the luminosity function (b).
4.2 V/V$_{\text{max}}$ Statistic

In order to assess the evolution in the comoving space density of radio sources we use the non-parametric V/V$_{\text{max}}$ method (Rowan-Robinson 1968; Schmidt 1968). V$_{\text{max}}$ is the volume over which the galaxy could have been observed given the selection limits. It allows the incorporation of additional selection criteria.

For a uniform distribution, the value of V/V$_{\text{max}}$ will be uniformly distributed between 0 and 1. Thus for such a sample the mean value is $\langle (V/V_{\text{max}}) \rangle = 0.5 \pm (12N)^{-1/2}$, where $N$ is the number of objects in the sample. $\langle (V/V_{\text{max}}) \rangle > 0.5$ indicates that the sources are biased towards larger distances, or an increase of the space density with redshift. $\langle (V/V_{\text{max}}) \rangle < 0.5$ indicates a deficiency in high redshift sources, or a decline in the space density with redshift. A constant comoving population is given by $\langle (V/V_{\text{max}}) \rangle = 0.5$ (Clewley & Jarvis 2004; Tasse et al. 2008; McAlpine & Jarvis 2011; McAlpine et al. 2013; Prescott et al. 2016).

Our sample is a matched radio/optical sample, thus we take into account both the optical and radio limits of the surveys, where V$_{\text{max}}$, the final maximum observable volume, is taken as the minimum from the optical and radio V$_{\text{max}}$ for each source:

$$V_{\text{max}} = \min(V_{\text{max,radio}}, V_{\text{max,optical}})$$  (3)

Where V$_{\text{max,radio}}$ and V$_{\text{max,optical}}$ represent the maximum observable volumes of the source in the radio and optical surveys respectively and are shown below:

$$V_{\text{max,radio}} = \sum_{i=1}^{n} V_{\text{max,radio},i}(z_{\text{max,radio},i}) \times C_i$$  (4)

$$V_{\text{max,optical}} = \sum_{i=1}^{n} V_{\text{max,optical},i}(z_{\text{max,optical},i}) \times C_i$$  (5)

V$_{\text{max,radio}}$ and V$_{\text{max,optical}}$ were computed from $z_{\text{max,radio}}$ and $z_{\text{max,optical}}$ as shown in equations 4 and 5 above. This is in a single redshift bin and that the sum goes over all the galaxies in a given redshift bin. The $z_{\text{max,radio}}$ and $z_{\text{max,optical}}$ represent the maximum observable redshifts of the source in the radio and optical surveys respectively. The k-correction to the V$_{\text{max,radio}}$ is a power law. We estimate $z_{\text{max,radio}}$ by running kcorrect (Blanton et al. 2003) which redshifts the best fitting SED template from the photometric redshift estimation procedure and determine the redshift where the template becomes fainter than our imposed a limiting magnitude of $r = 25$. The derivation of the radio completeness $C_{\text{r}}$ is given by $\epsilon(s)$ (see Ocran et al. (2019)). The $\epsilon(s)$ is the probability that a source with true flux density, $s$, will result in a detection. We measured this by inserting 3000 artificial point sources at a given true flux density at random positions into the residual map with the original sources removed. These sources populate the image with the same background noise and rms properties as the original source finding. We stressed in Ocran et al. (2019) that the field of view effect dominates the curve in the radio completeness correction (see Figure 7, Ocran et al. (2019)) since the analysis is incorporating the varying sensitivity limit across the field of view due to the GMRT primary beam. This represents the completeness of the radio source catalogue versus true flux density (see Ocran et al. 2019). In order to correct for the redshift incompleteness, we divided the distribution for the entire sample (i.e. light gray histogram see Figure 2) by the distribution for the sources with at least one diagnostic for AGN activity (i.e. blue histogram). We then corrected the RLF with this redshift success completeness, C$_{\text{z}}$.

This redshift incompleteness in our sample is mostly due to sources not being detected in the optical wavelength range, so that we cannot compute a reliable (photometric) redshift. We define the completeness correction factor $C_{\text{z}}$ (i.e see equations 4 and 5) as:

$$C = C_{\text{z}} \times C_{\text{f}}$$  (6)

C$_{\text{z}}$ is the redshift success completeness and C$_{\text{f}}$ is the completeness of the radio catalog.

In Figure 5 and Table 3 we show the mean V/V$_{\text{max}}$ statistic in bins of radio luminosity in the range $10^{20} < L_{610 \text{MHz}} < 10^{25} \text{ WHz}^{-1}$ for our SFG sample (see open black circles). For each bin we provide the number of sources (N) in the bin, mean (V/V$_{\text{max}}$), mean redshift ($\langle z \rangle$). The $\sigma = 1/\sqrt{2N}$ Avni & Bahcall (1980) are the statistical errors derived from the sample size. The dashed horizontal line shows the median (V/V$_{\text{max}}$). We calculate (V/V$_{\text{max}}$) to be $0.51 \pm 0.06$ for our SFGs. This value is not significantly different from 0.5, given the error of 0.06 thus averaged over luminosity there is no overall evidence for evolution in the number density of SFGs. However there is a clear trend of V/V$_{\text{max}}$ with radio luminosity. At faint radio luminosities $L_{610 \text{MHz}} < 10^{23} \text{ WHz}^{-1}$ the values are below 0.5 indicating a higher space density at low redshift. Conversely for high luminosity, $L_{610 \text{MHz}} > 10^{23} \text{ WHz}^{-1}$ there is evidence for positive evolution or higher space density at higher redshift. The strong evolution of the high luminosity radio sources was also detected by Clewley & Jarvis (2004)). McAlpine & Jarvis (2011) also found evidence of this strong evolution at high luminosities although their result is at a lower statistical significance due to the small size of their sample. Taken together the results indicate strong luminosity evolution with overall number density constant with redshift but more high luminosity sources and fewer low-luminosity objects at higher redshift.

4.3 Derivation of the Radio luminosity function (RLF)

We derive the radio LF($\Phi$) for our GMRT sample in five redshift bins using the standard $\frac{1}{V_{\text{max}}}$ method (Schmidt 1968).

As the GMRT mosaics have non-uniform sensitivity, the effective area of the survey changes as a function of the flux limit. The volume of space available to a source of a given luminosity V$_{\text{max,radio}}$ (L) has to be calculated by taking into account the variation of survey area as a function of flux.
5 COSMIC EVOLUTION OF THE SFG RADIO LUMINOSITY FUNCTION

In this section we explain the reasoning behind adopting the analytic form of our local luminosity function at 610 MHz to fit our data. We further describe how the evolution of SFG luminosity function out to $z \approx 1.5$ is constrained.

5.1 The local RLF

Figure 6 presents the local 610 MHz SFG luminosity function shown as open black circles. The sample is truncated at $z < 0.1$ to minimize the effects of evolution. The yellow plus and blue stars represent Mauch & Sadler (2007) and Condon et al. (2002) SFG volume densities scaled to 610 MHz using an $a = -0.8$. The dashed red line is the analytic fit performed by Novak et al. (2017) to the local radio LF of SFGs from several surveys with different observed areas and sensitivities.

![Figure 6](image-url)

Figure 6. The local 610 MHz SFG luminosity function. The yellow plus and blue stars represents Mauch & Sadler (2007) and Condon et al. (2002) SFG volume densities scaled to 610 MHz using an $a = -0.8$. The dashed red line is the analytic fit to the local 610 MHz SFG data. We also show the 610 MHz RLF for SFGs in the redshift range $0.002 < z < 0.1$ shown in open black circles in Figure A1.

An analytic function of the type described by Saunders et al. (1990)

$$
\Phi_\star(L) = \Phi_\star \left( \frac{L}{L_\star} \right)^{1-a} \exp \left[ -\frac{1}{2\sigma^2} \log^2 \left( 1 + \frac{L}{L_\star} \right) \right] 
$$

(8)

where the $L_\star$ parameter describes the position of the turnover of the power-law plus log-normal distribution, $\Phi_\star$ is the normalization, $a$ and $\sigma$ are the faint and bright ends of the distribution, respectively.

To obtain the analytic form of the local luminosity function that is used throughout this work we use the best fit parameters from Novak et al. (2017), who combined data from both wide and deep surveys to properly constrain both the faint and the bright end of the local LF form Condon et al. (2002), Best et al. (2005), Mauch & Sadler (2007) data using the form given in equation 8. The best fit parameters obtained by Novak et al. (2017), which we use throughout this work are $\Phi_\star = 3.55 \times 10^3\text{Mpc}^{-3}\text{dex}^{-1}$, $L_\star = 1.85 \times 10^{23}\text{WHz}^{-1}$, $a = 1.22$, $\sigma = 0.63$.

5.2 RLF as a function of $z$

We compare our results with literature values of SFG LF derived at 1.4 GHz and scaled down to 610 MHz assuming $a = -0.8$ to check the robustness of our LF. Figure 7 presents the radio luminosity functions of SFGs at $\nu = 610\text{MHz}$ in different redshift bins (black open circles). Scaled down luminosity functions from 1.4 GHz to 610 MHz by...
Smolčić et al. (2009a), McAlpine et al. (2013) and Novak et al. (2017) are shown as green plusses, orange pentagons and blue diamonds respectively in each panel.

We compare with LFs derived from Wilman et al. (2008) semi-empirical simulation of the SKA and Mancuso et al. (2017) models. The Mancuso et al. (2017) models were obtained by following the model-independent approach by Mancuso et al. (2016a); Mancuso et al. (2016b). These models are based on two main ingredients: (i) the redshift-dependent SFR functions inferred from the latest UV/far-IR data from HST/Herschel and related statistics of strong gravitationally lensed sources, and (ii) deterministic tracks for the co-evolution of star formation and BH accretion in an individual galaxy, determined from a wealth of multiwavelength observations (see Mancuso et al. (2017)). We also compare to SFG models (see open brown diamonds in Figure 7) from the Tiered Radio Extragalactic Continuum Simulation (T-RECS) by Bonaldi et al. (2019) who modeled the corresponding sub-populations, over the 150 MHz - 20 GHz range. Our results concurs with the results of these models from literature, especially to the Mancuso et al. (2017) models. The Mancuso et al. (2017) models are lower than that of our SFG LF. Also, the faint end of the Bonaldi et al. (2019) and Wilman et al. (2008) models are higher than our measured SFG LF.

The breakdown of the luminosity, number density ($\Phi(L/\text{Mpc}^{-3} \text{dex}^{-1})$) and the number of sources in each redshift bin is presented in Table 6. Our data have small Poissonian error bars due to the relatively large number of sources in each bin and as such the errors do not reflect all possible systematic effects.

5.3 RLF Evolution

Following Novak et al. (2017), we assume that the shape of the LF remains unchanged at all observed cosmic times and only allow the position of the turnover and the normalization to change with redshift. We used the Markov chain Monte Carlo (MCMC) algorithm module emcee (Foreman-Mackey et al. 2013), implemented in the LMFIT Python package (Newville et al. 2014) to perform a multi-variate fit to the data. We fit all redshift slices for evolution assuming two scenarios for the LF, one in which the luminosity of the radio sources is fixed and undergoes pure density evolution parametrized (PDE) by

$$\Phi_L(z) = (1+z)^{k_D} \Phi_0(L)$$

(9)

and another in which the number density of radio sources is fixed and the population undergoes pure luminosity evolution:

$$\Phi_L(z) = \Phi_0 \left( \frac{L}{(1+z)^{k_L}} \right)$$

(10)

where $\Phi_0$ is the LF at redshift $z$, $\Phi_L$ the normalization of the local LF, and $k_D$ and $k_L$ represent pure density and pure luminosity evolution parameters, respectively and denotes the strength of the evolution. Both the PLE and PDE models are common in the literature (e.g. see Condon 1984; Sadler et al. 2002, 2007; Gruppi et al. 2013; McAlpine et al. 2013). Studies have shown that true evolution might be a combination of both of these extremes (see, e.g. Yuan et al. 2016a,b; Novak et al. 2017). The best fit evolution parameters for each redshift bin obtained with this procedure are presented in Table 5. The LMFIT Python package first does the fitting by performing a non linear least-squares $\chi^2$ minimization to obtain the best fit $k_D$ and $k_L$ parameters. The emcee is then implemented to calculate the probability distribution for the parameters. From this we get the medians of the probability distributions and a 1σ quantile, estimated as half the difference between the 15.8 and 84.2 percentiles.

We also fit a continuous model the redshift dependence of the evolution parameters by adding a redshift dependent term to the $k_L$ and $k_D$ parameters in Equation 9 and Equation 10 (e.g. see Novak et al. 2017; Smolčić et al. 2017b; Novak et al. 2018; Ceraj et al. 2018). We fit a simple linear redshift dependent evolution model to all SFG luminosity functions in all redshift bins simultaneously given by:

$$\Phi(L,z) = (1+z)^{k_D+z\beta_D} \times \Phi_0 \left( \frac{L}{(1+z)^{k_L+z\beta_L}} \right).$$

(11)

where $k_D$, $k_L$, $\beta_D$ and $\beta_L$ are the various evolution parameters. Equation 11 considers the case with both density and luminosity evolution combined plus redshift dependence (i.e four free parameters ). We test pure density and pure luminosity evolution together via the procedure described above. The 68% confidence region by combining PDE and PLE fitting to the samples are shown with grey shaded are Figure 7.

Figure 8 presents best fit parameters obtained from fitting PLE model to the SFG luminosity functions. The second column of Table 5 presents values of the parameters (i.e. $k_L$) obtained from fitting PLE model to the SFG luminosity functions Open red circles show the evolution parameters obtained from independently fitting the assumed analytic form of the luminosity function in five redshift bins assuming pure luminosity evolution scenario whereas the same color line shows the results from the continuous fit (i.e. jointly fitting the RLF in the 5 redshift bins) assuming that the PE parameter evolves linearly with redshift by using Equation 11. The vertical error bars represent the median absolute deviation (MAD) (Rousseeuw & Croux 1993) of the MCMC samples. We derive $\text{SFG}_{10}$Mhz $\propto (1+z)^{2.95 \pm 0.19} - 0.59 \pm 0.15$ (i.e. $k_L = 2.95 \pm 0.19$) for 0.002 < $z$ < 1.5. With no uncertainties associated with their estimated value, Haarsma et al. (2000) have found that a SFG with $k_L = 2.74$ is a good representation of the evolution of their radio-selected SF galaxies. Smolčić et al. (2009a) derived 2.1 ± 0.2 or 2.5 ± 0.1 for SFG depending on the choice of the local LF (i.e. Sadler et al. (2002) or Condon (1989) local LFs). Strazzullo et al. (2010) derived $k_L = 2.9 \pm 0.3$ by studying a sample of 1.4 GHz ra-
Figure 7. Radio luminosity functions of SFGs at $\nu = 610\,\text{MHz}$ in different redshift bins (black open circles). The black dashed lines in each panel are the SFG models from Mancuso et al. (2017). The black squares represent the total SFG LF from the semi-empirical simulation of the SKA (Wilman et al. 2008). Luminosity functions computed for SFGs from the T-RECS (Bonaldi et al. 2019) simulations are shown as open brown diamonds. The local radio luminosity function of Mauch & Sadler (2007) is shown for reference as a solid black line in each panel. Scaled down luminosity functions from 1.4 GHz to 610 MHz by Smolčić et al. (2009a), McAlpine et al. (2013) and Novak et al. (2017) are shown as green pluses, orange pentagons and blue diamonds respectively in each panel. The solid red lines in each panel correspond to the median values of the MCMC samples and the shaded regions correspond to the 68% confidence region of the PLE fit (skyblue) and also the combination of PDE and PLE fitting (grey) to the samples. The redshift range and the median redshift are shown in each panel. Error bars are determined using the prescription of Gehrels (1986).
dio sources in the Deep SWIRE Field (DSF), reaching a luminosity function in five redshift bins assuming pure luminosity evolution scenario (see text for details). The vertical error bars represent the median absolute deviation (MAD) of the MCMC samples. The horizontal error bars denote the inter-quartile range (IQR) of redshift in each bin. The same color line shows the results from the continuous fit assuming that the PLE parameter evolves linearly with redshift.

Figure 8. Parameters obtained from fitting PLE model to the SFG luminosity functions. Open red circles show the evolution parameters obtained from fitting the assumed analytic form of the luminosity function in five redshift bins assuming pure luminosity evolution scenario (see text for details). The vertical error bars represent the median absolute deviation (MAD) of the MCMC samples. The horizontal error bars denote the inter-quartile range (IQR) of redshift in each bin. The same color line shows the results from the continuous fit assuming that the PLE parameter evolves linearly with redshift.

6 THE COSMIC STAR FORMATION HISTORY TRACED BY THE LOW-FREQUENCY SFG POPULATION

The relationship between the FIR luminosity and the SFR is complex, since stars with a variety of ages can contribute to the dust heating, and only a fraction of the bolometric luminosity of the young stellar population is absorbed by dust (e.g., see Lonsdale Persson & Helou 1987; Walterbos & Greenawalt 1996). By adopting the mean luminosity for 10–100 Myr continuous bursts, solar abundances, the Salpeter (1955) initial mass function (IMF) and assuming that the dust reradiates all of the bolometric luminosity yields:

\[
\frac{SFR_\text{IR}}{M_\odot \text{yr}^{-1}} = \frac{L_{\text{IR}}}{5.8 \times 10^9 L_\odot}
\]  \hspace{1cm} (12)

(see Kennicutt 1998; Bell 2003; Murphy et al. 2011b). To compute the SFRs, we use the redshift dependent \(q(z)\) parameter. This should account for these intrinsic observational limitations under the assumption of a linear IR-radio correlation given by:

\[
\frac{SFR_{610 \text{MHz}(z)}}{M_\odot \text{yr}^{-1}} = \mathcal{F}_{\text{IMF}} \times 10^{-24} 10^{q(z)} \left( \frac{L_{610 \text{MHz}}}{\text{WHz}^{-1}} \right)
\]  \hspace{1cm} (13)

where \(\mathcal{F}_{\text{IMF}} = 1\) for a Chabrier (2003) IMF and \(\mathcal{F}_{\text{IMF}} = 1.7\) for a Salpeter (1955) IMF. Novak et al. (2017) stresses that since low-mass stars do not contribute significantly to the total light of the galaxy, only the mass-to-light ratio is changed when the IMF adopted is Chabrier (2003). We followed Novak et al. (2017) and used the Chabrier (2003) IMF.

In Figure 10 we show SFR from the total infrared luminosity as a function of radio luminosity at 610 MHz for SFGs. We color code the SFGs with redshift and dotted line shows the SFR, when a non-evolving \(q\)-value (i.e. median \(q\)-value in Section 3.1) is assumed. Converting the radio luminosity to SFR as shown in equation 12 to equation 13, before performing the integration will yield the star formation rate density (SFRD) of a given epoch as shown in equation 14 below, as presented as well by Novak et al. (2017).

\[
SFRD = \int_{L_{\text{min}}}^{L_{\text{max}}} \phi_{\text{Lz}}(L_z,k_0) \times SFR(L) d(\log L_{610 \text{MHz}})
\]  \hspace{1cm} (14)

To derive the SFR density we need to compute the radio luminosity density and to convert our radio luminosities into SFRs, in Figure 9, we show the luminosity density for our

Figure 10. SFR density at 610 MHz as a function of radio luminosity (dotted line). The SFR is computed as \(SFR = \frac{L_{\text{IR}}}{5.8 \times 10^9 L_\odot} \times \mathcal{F}_{\text{IMF}} \times 10^{-24} 10^{q(z)} \left( \frac{L_{610 \text{MHz}}}{\text{WHz}^{-1}} \right)\) and the SFR density is computed as \(SFRD = \int_{L_{\text{min}}}^{L_{\text{max}}} \phi_{\text{Lz}}(L_z,k_0) \times SFR(L) d(\log L_{610 \text{MHz}})\). The blue diamonds in Figure 7 show the Novak et al. (2017) LF scaled down to 610 MHz. Their results are in agreement with our luminosity functions, with the their LF constraining the high luminosity end. By comparing their results with LFs derived using IR and UV selected samples and checking their robustness, they reported that their radio LF can be well described by a local LF evolved only in luminosity as \(L_{610 \text{MHz}} \propto (1+z)^{3.2 \pm 0.2}(0.33 \pm 0.08)^{z}\). These previous studies are broadly consistent with our radio derived PLE parameter and Table 4 presents a summary of the comparison.
5 redshift bins. The curves are the PLE (solid red) best fit to the 610 MHz data in each redshift bin. We numerically integrated the expression in equation 14 by taking the analytical form of the LF in each redshift bin and using the best fit evolution parameters shown in Figure 7. We integrated over the entire luminosity range by setting \( L_{\text{min}} = 0 \) and \( L_{\text{max}} = +\infty \). This ensures that the integral converges and that the major contribution to the SFRD arises from galaxies with luminosities around the turnover of the LF. From this approach, Novak et al. (2017) stresses that the entire radio emission is recovered and if the LF shape and evolution is well constrained, the SFRD estimate will be within the SFR calibration errors. We also performed the integration using the data constrained limits, where \( L_{\text{min}} \) and \( L_{\text{max}} \) correspond to the lowest and the highest value of the observed LF. This ensures that, any bias due to LF extrapolation toward higher or lower luminosities is removed (see Novak et al. (2017)).

We show our total SFRD derived by integrating the pure luminosity evolved LF in individual redshift bins as open black circles in Figure 11. Table 5 presents the best-fit evolution parameters obtained by the fitting local luminosity function to the redshift binned data assuming pure luminosity \( k_{1} \) evolution and the SFRD derived. We compare our SFRD results with other radio-based estimates in Figure 11. Smolčić et al. (2009a) derived the cosmic star formation history out to \( z = 1.3 \) using the local 20 cm LFs (Condon 1989; Sadler et al. 2002), purely evolved in luminosity, and best fit to the VLA-COSMOS data in four redshift bins (see yellow pluses and brown squares). SFRD obtained when \( L_{\text{min}} \) and \( L_{\text{max}} \) are data constrained limits (lower limits) are also shown (see lightblue squares). Lower limits obtained by Novak et al. (2017) are shown as green triangles. To create a consistent multi-wavelength picture, we also compare our work with results in the literature derived at infrared (IR) and ultraviolet (UV) wavelengths in Figure 11. All SFR estimates were rescaled to a Chabrier IMF where necessary. The curve from the review by Madau & Dickinson (2014), who performed a fit on a collection of previously published UV and IR SFRD data is shown as a solid black curve. The curve from Behroozi et al. (2013) who provide new fitting formulae for star formation histories based on a wide variety of observations is shown as dashed green curve is also shown. The constrained SFRD by Burgarella et al. (2013) taking into account dust obscuration using combined IR and UV LFs reported in Gruppioni et al. (2013) and Cucciati et al. (2012), respectively are shown as red crosses for the total SFRD, red shaded area for the IR SFRD and green shaded area for the UV SFRD. The grey shaded area denote the uncertainty for the SFRD derived from integrated total IR LF reported in Gruppioni et al. (2013) and Cucciati et al. (2012), respectively are shown as red crosses for the total SFRD, red shaded area for the IR SFRD and green shaded area for the UV SFRD.

### Table 5. Best-fit evolution parameters obtained by the fitting local luminosity function to the redshift binned data assuming pure luminosity \( k_{1} \) evolution and the star formation rate density derived.

| \( \text{Med}(z) \) | \( k_{1} \) | \( \text{SFRD} \ [M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}] \) | Lower limits |
|----------------|--------|----------------|-----------|
| 0.18^{+0.05}_{-0.07} | 2.88^{+0.48}_{-0.94} | 0.021^{+0.004}_{-0.003} | 0.014^{+0.004}_{-0.003} |
| 0.39^{+0.10}_{-0.18} | 2.89^{+0.49}_{-0.95} | 0.026^{+0.005}_{-0.004} | 0.018^{+0.004}_{-0.003} |
| 0.66^{+0.16}_{-0.22} | 2.77^{+0.46}_{-0.95} | 0.035^{+0.009}_{-0.008} | 0.023^{+0.009}_{-0.008} |
| 1.08^{+0.15}_{-0.21} | 2.67^{+0.41}_{-0.94} | 0.046^{+0.010}_{-0.009} | 0.036^{+0.010}_{-0.009} |
| 1.28^{+0.04}_{-0.06} | 2.57^{+0.40}_{-0.96} | 0.066^{+0.013}_{-0.007} | 0.053^{+0.013}_{-0.007} |

### 7 CONCLUSIONS

Over the last few years Bonzini et al. (2013), Padovani et al. (2015) and Smolčić et al. (2017a) have for the first time managed to carry out a complete census of populations contributing to the faint radio sky at 1.4 and 3.0 GHz with the JVLA. These were done over a relatively small (0.5 deg$^2$ and 2 deg$^2$ for JVLA-ECDFS and JVLA-COSMOS respectively) contiguous area reaching rms sensitivities (i.e. 6µJy and 2.5µJy at 1.4 and 3.0 GHz respectively) comparable to our study. Such datasets that provide images of the radio flux density over small regions at these sensitivities are still rare but will be achieved by the MeerKAT and SKA1 albeit over much larger areas. We study a sample of 1685 SFGs covering ~1.86 deg$^2$ down to a a minimum noise of
between the total infrared luminosity ($L_{IR}$) and the radio luminosity ($L_{radio}$) for the star-forming galaxies. We measure an evolution with redshift of the IRRC for 1.4 GHz radio luminosities to be $q_{IR} = 2.86 \pm 0.04(1 + z)^{-0.20+0.02}$, where $q_{IR}$ is the ratio between the total infrared luminosity ($L_{IR}$) and the 1.4 GHz radio luminosity ($L_{1.4\,GHz}$).

We study the infrared-radio correlation (IRRC) for the star-forming galaxies. We measure an evolution with redshift of the IRRC for 1.4 GHz radio luminosities to be $q_{IR} = 2.86 \pm 0.04(1 + z)^{-0.20+0.02}$, where $q_{IR}$ is the ratio between the total infrared luminosity ($L_{IR}$) and the 1.4 GHz radio luminosity ($L_{1.4\,GHz}$).

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We use the non-parametric V/Vmax test and the radio luminosity function to investigate the cosmic evolution of SFGs. Sadler et al. (2007) found evidence that low-luminosity radio sources experience mild evolution with an increase in their number density by a factor of $\sim 2$ at $z = 0.55$. Smolčić et al. (2009a) found a mild evolution of the low-power AGNs in the VLA-COSMOS survey out to $z \sim 1.3$. We construct the RLF at 610 MHz for our SFGs and find positive evolution. This is consistent with previous studies, for the SFG RLF scaled to 610 MHz from 1.4 GHz assuming a spectral index of $\alpha = -0.8$. The exact shape of the radio spectral energy distribution (SED) of SFGs is usually assumed to be a superposition of the steep synchrotron spectrum, described by a power law (see Condon 1992), even so, there are processes which can alter the shape of the spectra. Recent work by Lacki (2013) and Tisanić et al. (2019) have developed theoretical models describing an alternative picture to the simple power-law shape which includes spectral curvature. However, recent multi-frequency radio observations of representative samples of galaxies are needed to study the radio SED and understand the physical processes shaping it across redshifts.

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We have used the non-parametric V/Vmax test and the radio luminosity function to investigate the cosmic evolution of SFGs. Sadler et al. (2007) found evidence that low-luminosity radio sources experience mild evolution with an increase in their number density by a factor of $\sim 2$ at $z = 0.55$. Smolčić et al. (2009a) found a mild evolution of the low-power AGNs in the VLA-COSMOS survey out to $z \sim 1.3$. We construct the RLF at 610 MHz for our SFGs and find positive evolution. This is consistent with previous studies, for the SFG RLF scaled to 610 MHz from 1.4 GHz assuming a spectral index of $\alpha = -0.8$. The exact shape of the radio spectral energy distribution (SED) of SFGs is usually assumed to be a superposition of the steep synchrotron spectrum, described by a power law (see Condon 1992), even so, there are processes which can alter the shape of the spectra. Recent work by Lacki (2013) and Tisanić et al. (2019) have developed theoretical models describing an alternative picture to the simple power-law shape which includes spectral curvature. However, recent multi-frequency radio observations of representative samples of galaxies are needed to study the radio SED and understand the physical processes shaping it across redshifts.

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luminosity observations. Our LFs behave very well at high luminosities, where other samples (see e.g. Smolčić et al. (2009b)) show an excess of sources with respect to models. This can be interpreted as contamination due to AGN. This can be better addressed with better multi-wavelength data and better-proven AGN diagnostics. Our radio LFs can be well described by a local LF evolved only in luminosity as $L_{610\,\text{MHz}} \propto (1 + z)^{(2.95 \pm 0.19) - (0.50 \pm 0.15)z}$.

We converted our radio luminosities to SFRs using a redshift dependent IR-radio correlation. By integrating over the entire luminosity range the LF fits in various redshift bins, we derived the cosmic star formation density out to $z = 1.5$ for our SFG sample. Our estimates of the SFRD is consistent with previous measurements from the literature when all the SFR estimates are rescaled to a Chabrier IMF. Novak et al. (2017) assumed pure luminosity evolution for their LF, consistent with the measurements by Smolčić et al. (2009b) (and recent result by Gruppioni et al. (2013) assuming the redshift dependent IR-radio correlation parameter). All these studies found broad agreement between the radio SFRD evolution and UV/IR surveys, observing a steep decline from $z = 1$ to 0. Our sample reproduces this expected steep decline in the star formation rate density since $z \sim 1$. This work represents a benchmark for studying the evolution of the RLF and SFR function with cosmic time at the faint low-frequency regime in spite of our redshift limit.

In the near future we plan to undertake the exploitation of the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) Survey (Jarvis et al. 2016) with the MeerKAT SKA precursor (Jonas & MeerKAT Team 2016). MIGHTEE will survey well-studied extragalactic deep fields (E-CDFS, COSMOS, XMM-LSS and ELAIS-S1), totaling 20 square degrees at 1.4 GHz, to $\sim 2\,\mu\text{Jy/beam}$ rms. A survey matched in resolution and depth will be undertaken with the upgraded GMRT (Gupta 2014), and the present work will thus be precious to make the most of such GMRT data. It is our hope that a complete and expansive review of this topic will be able to do justice to the wealth of current and ongoing measurements contributing to our understanding of this aspect of galaxy evolution. An extensive compilation from the literature of SFR density measurements as a function of redshift will be investigated in future works. This will provide rich compilation of SFR density evolution which will help with a robust constraint for many investigations of galaxy evolution.

**APPENDIX A: LF**

The LFs obtained from the $\chi^2_{\text{ratio}}$ method for SFGs for the entire redshift range we consider (i.e. $0.002 < z < 1.5$) is shown in Figure A1 as open black circles. The local RLF from Mauch & Sadler (2007) is represented as black solid line in this figure for comparison. The total SFG RLF for our sample is higher than the SFG RLF of Mauch & Sadler (2007) scaled to 610 MHz assuming $\alpha = -0.8$. This is evident especially at the high luminosity end and can be attributed...
to cosmic evolution of the SFGs known to positively evolve with redshift (Mao et al. 2012). Also, this may be attributed to the sensitivity of our radio observations which allows us to probe the source population up to high redshifts. The open brown diamonds show LF’s computed for SFGs from T-RECS (Bonaldi et al. 2019) simulations. The faded black squares are RLF computed from the semi-empirical simulation of the SKA (Wilman et al. 2008). This is in good agreement with the RLF we compute for the SFG sample over the same redshift range. The breakdown of the results obtained for the 610 MHz RLF for SFGs from 0.002 < z < 1.5 is presented in Table A1.

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Table A1. 610 MHz RLF for SFGs from 0.002 < z < 1.5.

| Luminosity $L_{610\text{MHz}}$ (WHz$^{-1}$) | Number density $\Phi_{610}$ (Mpc$^{-3}$dex$^{-1}$) | Number |
|--------------------------------------------|-----------------------------------------------|--------|
| 20.28                                      | $7.51^{+14.64}_{-5.76} \times 10^{-3}$         | 1      |
| 20.77                                      | $1.02^{+12.00}_{-3.14} \times 10^{-3}$         | 4      |
| 21.32                                      | $3.25^{+3.25}_{-1.36} \times 10^{-3}$         | 6      |
| 21.67                                      | $2.63^{+0.24}_{-0.24} \times 10^{-3}$         | 20     |
| 22.09                                      | $3.64^{+0.26}_{-0.26} \times 10^{-3}$         | 69     |
| 22.44                                      | $2.67^{+0.17}_{-0.17} \times 10^{-3}$         | 147    |
| 22.82                                      | $1.60^{+0.38}_{-0.38} \times 10^{-3}$         | 237    |
| 23.19                                      | $5.85^{+0.55}_{-0.55} \times 10^{-4}$         | 255    |
| 23.61                                      | $2.64^{+0.09}_{-0.09} \times 10^{-4}$         | 258    |
| 23.95                                      | $9.04^{+0.09}_{-0.09} \times 10^{-5}$         | 209    |
| 24.33                                      | $1.86^{+0.18}_{-0.18} \times 10^{-5}$         | 74     |
| 24.66                                      | $1.41^{+0.10}_{-0.10} \times 10^{-6}$         | 6      |
| 25.00                                      | $2.33^{+3.43}_{-2.63} \times 10^{-7}$         | 1      |

The listed luminosity values represent the median luminosity of the sources in the corresponding luminosity bin.

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Figure A1. The 610 MHz RLF for SFGs in the redshift range 0.002 < z < 1.5 shown in open black circles. The local RLF of Mauch & Sadler (2007), which has been converted to 610 MHz from 1.4 GHz assuming a spectral index of α = −0.8, is shown in black line. The LF’s computed for SFGs from T-RECS (Bonaldi et al. 2019) simulations are shown as open brown diamonds. Error bars are determined using the prescription of Gehrels (1986). The lower panel shows the luminosity distribution with the number of sources in each bin indicated on the bar.

| Local LF (SFG) | GMRT SFG | SKADS (SFG) | Bonaldi + 18 |
|----------------|----------|-------------|--------------|
| ~ 1.86 deg²   | σ_\text{TBS} ~ 50 µJy |               |              |

\[ \Phi_{610}(\text{Mpc}^{-3}\text{dex}^{-1}) = \frac{1}{10^{11}} \]
