The far-infrared/radio correlation for a sample of strongly lensed dusty star-forming galaxies detected by Herschel

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ABSTRACT

We investigate the radio-far infrared (FIR) correlation for a sample of 28 bright high-redshift (1 ≤ z ≤ 4) star-forming galaxies selected in the FIR from the Herschel-ATLAS fields as candidates to be strongly gravitationally lensed. The radio information comes either from high sensitivity dedicated Australia Telescope Compact Array observations at 2.1 GHz or from cross-matches with the FIRST survey at 1.4 GHz. By taking advantage of source brightness possibly enhanced by lensing magnification, we identify a weak evolution with redshift out to z ≤ 4 of the FIR-to-radio luminosity ratio q_{FIR}. We also find that the q_{FIR} parameter as a function of the radio power L_{1.4GHz} displays a clear decreasing trend, similarly to what is observed for optically/radio selected lensed quasars found in literature, yet covering a complementary region in the q_{FIR} − L_{1.4GHz} diagram. We interpret such a behavior in the framework of an in-situ galaxy formation scenario, as a result of the transition from an early dust-obscured star-forming phase (mainly pinpointed by our FIR selection) to a late radio-loud quasar phase (preferentially sampled by the optical/radio selection).

Key words: gravitational lensing: strong – galaxies: star formation – quasars: general – radio continuum: galaxies – submillimetre: galaxies

1 INTRODUCTION

For several decades the rest-frame 1.4 GHz radio luminosity density \(L_{1.4 \text{GHz}}\) (W Hz\(^{-1}\)) emitted by bright dusty star-forming galaxies has been associated to their far infrared (FIR) luminosity \(L_{\text{FIR}}\) (8-1000 \(\mu\)m rest-frame) in terms of an empirical relation between these two quantities, namely the FIR-radio correlation (Helou et al. 1985, Yun et al. 2001). Such a relation is found to be roughly linear across ~ 3 orders of magnitude in luminosity 9 ≤ log \((L_{\text{FIR}}/L_{\odot})\) ≤ 12.5 with a rather low 1σ scatter ≤ 0.26 dex; it is often described via the parameter q_{FIR} (e.g. Yun et al. 2001, Magnelli et al. 2015) defined as:

\[
q_{\text{FIR}} = \log \left( \frac{L_{\text{FIR}} [\text{W}]}{3.75 \times 10^{12} [\text{L}_{1.4 \text{GHz}} [\text{W} \text{Hz}^{-1}]]} \right).
\]

The tightness of this relation can be ascribed to the common origin of the radio and FIR emissions as interpreted by calorimetric models (Lacki & Thompson 2010). In this framework, galaxies are assumed to be optically-thick to the UV light coming from young new born stars, which is absorbed by the dust in the interstellar medium and then re-radiated in the FIR regime. At the end of their lives, the same massive stars explode as Type II supernovae producing cosmic ray electrons and positrons, radiating most of their energy in the radio band through synchrotron emission before escaping the galaxy. Additionally, a secondary component of the radio emission comes from the free-free contribution originated by the hot and ionized HI regions.

The FIR-radio correlation is well established in the local universe (Helou et al. 1985, Yun et al. 2001, Jarvis et al. 2010, Smith et al. 2014, Molnár et al. 2017, Wang et al. 2019). Its apparent tightness encouraged the use of radio emission as an unbiased tracer of obscured star formation in dusty galaxies (Kennicutt & Evans 1984, 1989). This correlation is also observed at high redshift (1 ≤ z ≤ 3), where a decreasing trend of q_{FIR} with redshift is identified (e.g. Yun et al. 2001, Magnelli et al. 2015). The tightness of this relation can be ascribed to the common origin of the radio and FIR emissions as interpreted by calorimetric models (Lacki & Thompson 2010). In this framework, galaxies are assumed to be optically-thick to the UV light coming from young new born stars, which is absorbed by the dust in the interstellar medium and then re-radiated in the FIR regime. At the end of their lives, the same massive stars explode as Type II supernovae producing cosmic ray electrons and positrons, radiating most of their energy in the radio band through synchrotron emission before escaping the galaxy. Additionally, a secondary component of the radio emission comes from the free-free contribution originated by the hot and ionized HI regions.

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2012), and prospectively as a probe to obtain a comprehensive view of the cosmic star formation history up to very high redshift (Madau & Dickinson 2014, Novak et al. 2017, Delhaize et al. 2017). This is, in fact, one of the key science drivers of the SKA and of its pathfinder telescopes such as ASKAP and MeerKAT (e.g., Jarvis et al. 2015) and of the next-generation Very Large Array (ngVLA), focused on the investigation of the emission mechanisms that power the radio continuum emission in galaxies (Murphy 2019).

For example, early science data at 1.3 GHz from the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE, Jarvis et al. 2016) survey have been recently analysed in An et al. (2021), together with VLA and GMRT radio data, to investigate the radio spectral properties and the FIRRC for a sample of 2094 SFGs in the COSMOS field. Moreover, future observations with SKA will enable detailed investigations of magnetic fields in galaxies, which can be particularly relevant in the FIRRC especially in the low star formation rate (SFR) regimes (Schleicher & Beck 2016).

To achieve this goal, however, it is necessary to set on a firm basis the connection between radio and FIR emission (hence star formation), and to assess its redshift dependence, which has been strongly debated in last decades. From a theoretical perspective, an evolution in redshift is expected as a consequence of either the additional energy losses of the cosmic rays interacting with the cosmic microwave background photons through inverse Compton scattering (e.g Murphy 2009; Lacki & Thompson 2010) or because of the co-evolution of AGNs in dusty environments with ongoing star formation in the early stages of galaxy evolution (Lapi et al. 2018). In fact, sources whose radio emission is dominated by nuclear activity show up as outliers of the FIR-radio correlation (Sopp & Alexander 20191, Stacey et al. 2018). A \( q_{\text{FIR}} = 1.8 \) was proposed by Condon et al. (2002) as the boundary between star-formation and (radio-loud) AGN-dominated radio emission.

From an observational point of view, the evolution is far from being settled. On the one hand, different works found no significant evidence of a trend with redshift (e.g. Sargent et al. 2010). On the other hand, several authors pointed out the presence of a slight decline of the \( q_{\text{FIR}} \) parameter: Magnelli et al. (2015) report evidence of a weak redshift evolution in a mass-selected sample of galaxies, rendered as \( q_{\text{FIR}} \propto (1 + z)^{-0.12\pm0.04} \); a similar result was found by Basu et al. (2015) for a sample of blue cloud galaxies at \( z \leq 1.2 \); Tabatabaei et al. (2016) studied the radio continuum emission from the KINGFISH sample of nearby galaxies finding that the FIR to 1-10 GHz luminosity ratio could decrease with the star formation rate, suggesting a decrease of the ratio at high redshifts where mostly luminous/star forming galaxies are detected; more recently, Ocran et al. (2020) analysed the radio properties of 1685 star-forming galaxies selected at 610 MHz with the GMRT, inferring an evolution \( q_{\text{FIR}} \propto (1 + z)^{-0.2\pm0.02} \) up to \( z \sim 1.8 \); Delhaize et al. (2017) found \( q_{\text{FIR}} \propto (1 + z)^{-0.19\pm0.01} \) for galaxies selected with the VLA at 3 GHz; Calistro Rivera et al. (2017) obtained \( q_{\text{FIR}} \propto (1 + z)^{-0.15\pm0.03} \) for a sample of star-forming galaxies obtained with Low Frequency Array (LOFAR) at 150 MHz.

This observed evolution would imply that high-z (\( z \geq 1 \)) star forming galaxies present somehow a more pronounced radio emission (or a lower FIR luminosity) compared to their local counterparts. Other studies instead argued on the possibility that the observed trend with the redshift may be a consequence of selection effects (e.g. Sargent et al. 2010, Bourne et al. 2011, Molnár et al. 2021), which can be ascribed to the difference in depth between radio and FIR surveys and to flux-limited samples or to selections biased towards more massive galaxies, as recently reported by different authors (Delvecchio et al. 2021, Smith et al. 2021, Bonato et al. 2021). In fact, investigations at higher redshifts, carried out up to \( z \geq 2 \) (Ivison et al. 2010a, Thomson et al. 2014, Magnelli et al. 2015) have been limited by the availability of very deep radio data and/or redshift measurements. In this sense, selection biases can be minimized in homogeneous populations of FIR/submm galaxies (e.g. Aligera et al. 2020). In fact, FIR/submm surveys are poorly affected by dust obscuration and feature almost constant flux densities across a wide range of redshifts (0 \( \leq z \leq 10 \), Blain et al. 2002). The resulting strong negative K-correction allowed the detection of such a population predominantly at high redshifts (\( z \sim 2 – 3 \)) up to \( z \sim 6 \). It has also become clear that the nuclear activity has a crucial impact on the host galaxy and its interstellar medium through the action of energy/momentum feedback (i.e., radio jets), affecting the scatter of the FIR-radio correlation (Sopp & Alexander 1991) and (probably) its redshift evolution. In this sense, the study of dusty star-forming galaxies in the (sub)mm and radio bands is crucial to characterize the interplay between nuclear activity and star formation; high-z dusty galaxies are however compact, with typical intrinsic sizes of a few tenths of an arcsec (Pantoni et al. 2021), hence very hard to resolve.

In recent years, a big step forward has been made thanks to large-area submm surveys which have been used to efficiently select strongly lensed galaxies at high redshift. Lensing enables the observation of regions in the luminosity-redshift space of these sources, that would be otherwise unattainable with current instrumentation or would require an excessive amount of integration time. Indeed, the magnifications of apparent luminosity and angular size by the effect of a foreground lens, offer the unique possibility of studying down to sub-kpc scales the properties of objects otherwise not exceptionally bright, massive, or peculiar, and belonging to the bulk of the galaxy population at the peak of the cosmic star formation history (\( z \sim 2 \), Madau & Dickinson 2014). In FIR/submm bands, high-z lensed dusty galaxies are particularly bright, while a negligible signal comes from the foreground lens, which is often a massive evolved elliptical at \( z \leq 1 \). Also the obscuration from the foreground lens that limits the investigation of the background galaxy in the optical is negligible in the FIR/submm domain. The capabilities of the Herschel Space Observatory to select dusty star-forming lensed galaxies have been amply proved. Wardlow et al. (2013) identified 11 lensed galaxies over the 95 deg\(^2\) of the Herschel Multi-tiered Extragalactic Survey (HiRECES; Oliver et al. 2012); other 27 candidate lensed galaxies were found by Nayyeri et al. (2016) in the HerMES Large Mode survey (HeLMS; Oliver et al. 2012) and in the Herschel Stripe 82 Survey (HeS8; Viero et al. 2014). The Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS; Eales et al. 2010) is the widest area (600 deg\(^2\)) extragalactic survey undertaken by Herschel and has provided a sample of more than a hundred thousand dusty galaxies at high redshift. During the Science Demonstration Phase (SDP), covering a 16 deg\(^2\) portion of the sky, Negrello et al. (2010) selected the first sample of 5 strongly lensed galaxies in H-ATLAS. Negrello et al. (2017) further exploited this survey to extract a catalog of 80 candidate strongly lensed dusty star-forming galaxies brighter than 100 mJy at 500 m. The capabilities of the Herschel Space Observatory to select dusty star-forming lensed galaxies have been amply proved. Wardlow et al. (2013) identified 11 lensed galaxies over the 95 deg\(^2\) of the Herschel Multi-tiered Extragalactic Survey (HiRECES; Oliver et al. 2012); other 27 candidate lensed galaxies were found by Nayyeri et al. (2016) in the HerMES Large Mode survey (HeLMS; Oliver et al. 2012) and in the Herschel Stripe 82 Survey (HeS8; Viero et al. 2014). The Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS; Eales et al. 2010) is the widest area (600 deg\(^2\)) extragalactic survey undertaken by Herschel and has provided a sample of more than a hundred thousand dusty galaxies at high redshift. During the Science Demonstration Phase (SDP), covering a 16 deg\(^2\) portion of the sky, Negrello et al. (2010) selected the first sample of 5 strongly lensed galaxies in H-ATLAS. Negrello et al. (2017) further exploited this survey to extract a catalog of 80 candidate strongly lensed dusty star-forming galaxies brighter than 100 mJy at 500 m.
compare our result to that of the lensed quasar sample by Stacey et al. (2018), highlighting the complementarity of the two selections and presenting a physically-motivated interpretation in the framework of an in-situ galaxy evolution model (see 4). Finally, we summarise our findings (see Sec. 5).

In this work we adopt the standard flat ΛCDM cosmology (Planck Collaboration et al. 2020) with rounded parameter values: matter density $\Omega_M = 0.32$, dark energy density $\Omega_L = 0.68$, baryon density $\Omega_b = 0.05$, Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$ with $h = 0.67$, and mass variance $\sigma_8 = 0.81$ on a scale of 8 $h^{-1}$ Mpc.

2 THE SAMPLE

2.1 The H-ATLAS lensed galaxies

Negrello et al. (2017) extracted a sample of 80 bright FIR/submm-selected galaxies with flux density $S_{\nu, \text{mm}} > 100$ mJy from the H-ATLAS fields. The SPIRE photometry is obtained from the point-source Herschel/SPIRE catalogues of the H-ATLAS Data Release 1 and 2, described in Valiante et al. (2016) and Maddox et al. (2017). The catalogues have been created identifying the 2.5 $\sigma$ peaks in the SPIRE 250 $\mu$m maps, which are then used as position priors to measure flux densities in the other SPIRE bands. The instrumental and confusion noise have been minimized through the use of a matching filter for the creation of the maps from which fluxes have been extracted. Only sources with a signal-to-noise ratio $> 4$ in at least one of the three SPIRE bands have been included in the final catalogue. As described in Negrello et al. (2017), extended sources have been detected through optical images and treated as contaminants, therefore are not included in the sample of 80 candidate lensed galaxies. The sample galaxies feature FIR (8-1000 $\mu$m) luminosities in the range $13 \leq \log(L_{\text{FIR}}/L_\odot) \leq 14$ (uncorrected for lens magnification). They span a redshift range $1 \leq z \leq 4.5$ (29 spectroscopic, 51 photometric redshifts) with a median value $z_{\text{med}} = 2.5$. However, to date, only 21 of the 80 candidates in Negrello et al. (2017) sample have been confirmed to be genuine strongly lensed objects through detailed optical/near-infrared (with HST and Keck) or submm (with SMA) images of their structure, together with spectroscopic redshift measurements of the background lensed galaxy and of the foreground lens. For other 8 sources the lensing scenario is strongly supported by the redshift difference of optical/NIR and submm galaxies along the line of sight. The remaining sources are classified as uncertain because they still miss proper follow-up that could confirm their lensed nature.

Some of the sources in the sample have been individually studied in detail exploiting multi-wavelength high-resolution observations. For example, Enia et al. (2018) performed lens modelling and source reconstruction for 13 of the 500 $\mu$m-selected lensed galaxies in H-ATLAS using high-resolution SMA observations at 870 $\mu$m (Bussmann et al. 2013). SDP.81 has been the target of observations and modelling in the ALMA long-baseline campaign (Partnership et al. 2015, Rybak et al. 2015b, Rybak et al. 2015a, Dye et al. 2015, Swinbank et al. 2015, Tamura et al. 2015, Hatsukade et al. 2015, Hezaveh et al. 2016). These studies led to the reconstruction of the matter distribution of the foreground lens through the detection of low-mass substructures, together with the pixelated surface brightness distribution of dust in the lensed source. Thanks to ALMA CO and CII spectroscopic data, it was also possible to measure with high precision the gas mass distribution and the kinematics of the clumps, revealing a disturbed morphology of the stellar, gas and dust components (see also Rybak et al. 2020). SDP.11 ALMA high-resolution images of the continuum at 1.1 mm and of CO(6-5) (Wong et al. 2017) have been combined with X-ray band observations from Chandra to reconstruct the morphology and characterize the nuclear emission (Massardi et al. 2017).

2.2 ATCA follow-up

The sample in the H-ATLAS South Galactic Pole field comprises 30 sources with $22 < RA < 0h$ and $-36 < \delta < -28$. All these are candidate, i.e. not yet confirmed, strongly lensed galaxies. Observations were centered at 2.1 GHz with a 2 GHz bandwidth and were carried out with the Australia Telescope Compact Array (ATCA) on 2017 December 14th and on 2019 July 31th respectively with a 6 km and a 750 m East-West configurations. The corresponding largest angular scales (LAS) are 3.6 and 1.8 arcmin for the first and second configuration respectively. The expected resolution is $\sim 10$ arcsec if the farthest antenna, CA06, is included in the data, as in our case. In 2017 we got 12 allocated hours that allowed us to perform $\sim 7 \times 2$ min cuts on each target. In 2019 we performed $2 \times 2$ min at least on each source for a total of 4 observing hours. The observing strategy allowed enough coverage of the uv domain to recover suitable images of our targets. The weather and system conditions were excellent in both the observing epochs.

Data editing, calibration and imaging is performed using Miriad (Sault et al. 1995). Flagging of data is fully automatic and exploits the PGFLAG task, and calibration follows common procedures for 16 cm band data-sets. Manual checking confirms that all the major RFI features are removed from the data, flagging more than 30% of the data, but still recovering a 0.06 mJy beam$^{-1}$ theoretical noise level ($\lambda\nu$). PKS1934-638 was observed as bandpass and flux calibrator. Two phase calibrators were observed during the 12 hours and 4 hours observations (PKS0008-421 and PKS2255-282) and their solutions are merged to correct the data phases as a function of time.

The two data-sets are combined during the imaging process with the task UVAVER in order to improve the uv-sampling and the dynamical range of the final image. We perform self-calibration during the imaging process in each observed field, exploiting the presence of several bright and point-like sources in the large field of view (22 arcmin FWHM), allowing the improvement of the overall signal-to-noise. Flux densities ($S_{\text{image}}$) and image noise ($\sigma_{\text{image}}$) are then extracted from the Briggs-weighted continuum images with robust factor of 0.5. The average synthesized beam is $\sim 7.4 \times 3.9$ arcsec. Noise is computed as

$$\delta S_{\text{image}} = \sqrt{(\sigma_{\text{image}})^2 + (0.05 \times S_{\text{image}})^2}$$

(2)

to consider the calibration errors. For later use we convert the ATCA flux densities from 2.1 GHz to 1.4 GHz assuming a power law spectrum $S_{\nu} \propto \nu^\alpha$ with average radio spectral index $\alpha = -0.7 \pm 0.14$, consistently with Stacey et al. (2018).

2.3 FIRST catalogue counterparts

The FIRST (Faint Images of the Radio Sky at Twenty-cm; Becker et al. 1995) survey, performed with the VLA reaches a typical rms of 0.15 mJy beam$^{-1}$ and a resolution $\sim 5$ arcsec comparable with those of our observations. FIRST overlaps with the Equatorial and North Galactic Pole H-ATLAS fields, thus complementing our search for radio counterparts for the Negrello et al. (2017) sample. The cross-match with the FIRST catalogue within 10 arcsec of the Herschel-ATLAS position yields 8 potential counterparts, while for
Figure 1. Cutouts of NIR images with the best available angular resolution centred on the Herschel positions for the 11 sources with an ATCA cross-match. Contours at $3,5,7,9\sigma$ levels are showed in gold for the radio and cyan for ALMA. Circles are the SPIRE position with a $3\sigma_{pos}$ radius. RA and Dec are reported in Deg units. The postage stamps are 30x30 arcsec.
Figure 2. Cutouts of NIR images with the best available angular resolution centred on the Herschel positions for the 16 sources with a FIRST cross-match. Contours at 3,5,7,9σ levels are showed in gold for FIRST and cyan for ALMA. Circles are the SPIRE position with a 3σ_{pos} radius. RA and Dec are reported in Deg units. The postage stamps are 30x30 arcsec.
12 objects we find a clear $\geq 3\sigma$ signal in the FIRST maps, within the H-ATLAS beamsize. For one of the matched source, namely H-ATLAS J142935.3-002836, the FIRST flux density value has been replaced with the more reliable one coming from the JVLA 7 GHz high resolution ($0.3$ arcsec) and high sensitivity ($10\, \mu Jy\, beam^{-1}$) observations described in Messias et al. (2014) (converted at 1.4 GHz).

Observations at 6.89 GHz from the JVLA are available for one additional source (H-ATLASJ133542.9+300401) and are described in details by Nayyeri et al. (2017). The image reaches an rms of 7.8 $\mu Jy\, beam^{-1}$ and a beam size of 1.01$\times$0.81 arcsec; for our analysis we use the flux density in the above paper already reported at 1.4 GHz (see Table 1 in Nayyeri et al. 2017).

H-ATLASJ090311.6+003907 (SDP.81) is detected in the FIRST catalogue, was observed by the Extended Very Large Array (EVLA) at 8.4 GHz (Valtchanov et al. 2011, Rybak et al. 2015b). However, its radio emission is likely to be originated from the AGN hosted by the foreground lens (Tamura et al. 2015, Rybak et al. 2020); for this reason it has been excluded a priori as a possible counterpart.

2.4 Counterparts selection

The detected sources display a variety of radio morphologies: some of them show a compact radio emission, others instead feature a more extended structure or even multiple components, but the angular resolution of the observations is not enough to resolve any of the arcs possibly associated to lensing effects.

For this reasons, in order to establish whether a radio source is correctly assigned as a counterpart of our selected Herschel sample, we selected radio detections with at least $> 3\sigma_{image}$ confidence level and then consider their position with respect to the optical/IR and the mm high angular resolution imaging.

We consider as a counterpart only the component nearest to the SPIRE peak position, whose radio detected emission overlaps with sources detected the in NIR or mm, even though this can result in a underestimation of the radio luminosity in case of multiple component radio sources. In the NIR we exploit HST/WFC3 wide-J filter F110 maps described in Negrello et al. (2014) and more recent snapshot observations covering the Equatorial and Southern fields (PI: Marchetti L., 2019), both reaching an angular resolution of $\sim 0.13$ arcsec. The remaining sources are observed by the UK Infrared Deep Sky Survey Large Area Survey (UKIDSS-LAS; Lawrence et al. 2007) and the VISTA Kilo-Degree Infrared Galaxy Survey (VIKING; Edge et al. 2013), reaching angular resolutions $\leq 1$ arcsec. Millimetric high resolution images come from the ALMA Science Archive: some of the sources located in the South Galactic Pole have been target of Band 4 follow-ups at $\sim 1.7$ arcsec, while for objects in the Northern and Equatorial fields we make use of the images found in bands 4, 6 and 7, with highest angular resolutions spanning from $\sim 1.2$ to $< 0.1$ arcsec. For sources without high resolution imaging we compared the uncertainties on the radio positional accuracy (Becker et al. 1995) with respect to the one from SPIRE/250 $\mu m$ (Bourne et al. 2011), with a $\sim 3\sigma$ tolerance. We include only objects showing a superimposition between the two centroids and/or between the SPIRE positional uncertainty and the radio detection.

Following the above criteria we find 11 and 17 sources in...
ATCA and FIRST respectively, showed in Fig. 1 and Fig. 2. Please note that the HST/WFC3 maps reported here do not take into account the well knew positional offset between ALMA and HST counterparts (Dunlop et al. 2016, Rujopakarn et al. 2016). Therefore, combining ATCA follow-up and FIRST cross-matches we collected radio measurements for 28 out of the 80 galaxies in the original sample by Negrello et al. (2017), that will constitute our reference in the present paper.

For the remaining objects we define an upper limit for detection at 3σ from the noise at the position of the sources in the FIRST images and as 3σimage for ATCA images. Table 1 summarises the radio and FIR photometry for our sample.

Finally, few considerations need to be done. First, we would like to stress that in this paper we rely only on the available archived radio data without focusing into descriptions of the single objects. In our analysis we take into account the information available in the literature for the confirmed cases, but for the remaining unconfirmed ones in an accurate lensing modelling and/or higher angular resolution observations, it is not possible to confirm whether or in which fraction the radio emission is associated to the lensed object. This is also valid for the SPIRE flux densities in the unconfirmed cases. Indeed, as showed in Figures 1 and 2, multiple sources entering the Herschel beam are detected in the ALMA (sub- mm maps, leading to a possible overestimation of the effective FIR luminosity of the actual counterpart. A fraction of low resolution sub-mm detected sources is indeed expected to be composed by multiple ALMA sources (Hodge et al. 2013, Smail & Walter 2014, Bussmann et al. 2015). Here we assume that the observed SPIRE flux density is mostly originated by the same object and that no strong FIR contamination from possible nearby sources is present. In any case, this should not affect the objects already confirmed to be lensed. In fact, we expect the FIR luminosity of the lensed galaxies in our sample to be magnified by a factor spanning the range ~ 3 – 10 (Negrello et al. 2017, Enia et al. 2018), with a negligible contribution from possible additional unlensed sources entering the Herschel beam.

2.5 Physical properties of the sample

The rest-frame radio luminosity $L_{1.4 \text{GHz}}$ at 1.4 GHz for each source (see Table 2) is computed as

$$L_{\nu, e} = \frac{4\pi D_L^2(z)}{(1+z)^{\alpha}} \frac{\nu_e}{\nu_0} S_{\nu, e},$$

(3)

where $S_\nu \propto \nu^\alpha$ is the monochromatic flux density at a certain frequency and $\alpha$ is assumed to be -0.7 as the typical value at 1.4 GHz for FIRST (Kimball & Ivezić 2008), $v_e$ and $v_0$ are the emitted and the observed frequency, and $D_L$ is the luminosity distance computed.

\[\text{Table 1. Radio and FIR properties of the candidate and confirmed lensed galaxies with a counterpart in the radio bands. Columns are as follows: H-ATLAS IDs; Herschel/SPIRE flux densities; source redshift; lens classification from Negrello et al. (2017): (A) confirmed dusty lensed, (B) likely to be lensed, (C) uncertain; radio flux densities at 1.4 GHz; origin of the radio counterpart (images, catalogue or literature); distance (in arcseconds) of the radio peak from the Herschel position, if available.} \]
The resulting FIR luminosities (uncorrected for lens magnification) and dust temperatures are shown in Figure 3. The FIR luminosities span the range $1.3 \times 10^{13} \leq L_{\text{FIR}} \leq 1.1 \times 10^{14} L_\odot$, with a median value of $L_{\text{FIR}} \sim 3.5 \times 10^{13} L_\odot$. The median value of the dust temperature for the total sample of candidate strongly lensed galaxies is $T_{\text{dust}} = 35.2 \pm 2.1$, consistently with what was found by Negrello et al. (2017) for the same sample.

### Table 2. 1.4 GHz and FIR luminosities (uncorrected for lensing magnification effects) and $q_{\text{FIR}}$ parameter for the 28 galaxies in our sample.

| #H-ATLAS ID | log($L_{1.4\text{GHz}}$) ($L_\odot$) | log($L_{\text{FIR}}$) [W Hz$^{-1}$] | $q_{\text{FIR}}$ |
|-------------|------------------------------------|---------------------------------|-----------------|
| J000007.4-334059 | 25.86$\pm$0.04 | 13.40$\pm$0.05 | 1.55$\pm$0.15 |
| J000722.1-352014 | 24.62$\pm$0.06 | 13.11$\pm$0.02 | 2.49$\pm$0.13 |
| J000912.7-300807 | 24.29$\pm$0.10 | 13.24$\pm$0.01 | 2.96$\pm$0.23 |
| J005132.8-301848 | 25.13$\pm$0.08 | 13.59$\pm$0.07 | 2.47$\pm$0.24 |
| J010250.8-311723 | 24.77$\pm$0.07 | 13.41$\pm$0.03 | 2.64$\pm$0.17 |
| J012407.3-284134 | 25.37$\pm$0.05 | 13.58$\pm$0.04 | 2.20$\pm$0.14 |
| J013004.0-305513 | 25.07$\pm$0.05 | 13.15$\pm$0.03 | 2.08$\pm$0.12 |
| J013239.9-330906 | 24.98$\pm$0.10 | 13.48$\pm$0.07 | 2.50$\pm$0.26 |
| J085359.9+015537 | 25.46$\pm$0.06 | 13.68$\pm$0.03 | 2.22$\pm$0.14 |
| J090302.9-014127 | 25.09$\pm$0.15 | 13.72$\pm$0.03 | 2.64$\pm$0.35 |
| J090740.0-004200 | 25.19$\pm$0.05 | 13.57$\pm$0.01 | 2.39$\pm$0.12 |
| J091043.0-000022 | 25.22$\pm$0.08 | 13.55$\pm$0.02 | 2.33$\pm$0.20 |
| J091840.8+020348 | 26.25$\pm$0.02 | 13.39$\pm$0.06 | 1.14$\pm$0.15 |
| J114637.9-001132 | 25.86$\pm$0.06 | 14.03$\pm$0.05 | 2.17$\pm$0.18 |
| J120311.1-011253 | 25.54$\pm$0.08 | 14.00$\pm$0.06 | 1.86$\pm$0.23 |
| J125135.3+261457 | 26.20$\pm$0.05 | 15.37$\pm$0.09 | 1.86$\pm$0.23 |
| J125759.5+224558 | 25.01$\pm$0.07 | 13.21$\pm$0.02 | 2.20$\pm$0.17 |
| J131540.6+262322 | 25.51$\pm$0.07 | 13.71$\pm$0.07 | 2.50$\pm$0.23 |
| J132427.0+284449 | 25.46$\pm$0.04 | 13.37$\pm$0.04 | 1.91$\pm$0.12 |
| J133255.7+342207 | 25.42$\pm$0.07 | 13.33$\pm$0.04 | 1.92$\pm$0.18 |
| J133542.9+300401 | 24.75$\pm$0.07 | 13.45$\pm$0.05 | 2.70$\pm$0.20 |
| J133649.9+291800 | 25.37$\pm$0.09 | 13.59$\pm$0.03 | 2.22$\pm$0.18 |
| J134429.4+303034 | 25.59$\pm$0.05 | 13.83$\pm$0.04 | 2.24$\pm$0.15 |
| J142413.9+022303 | 25.85$\pm$0.09 | 13.93$\pm$0.12 | 1.99$\pm$0.34 |
| J142935.3-002836 | 25.15$\pm$0.10 | 13.57$\pm$0.01 | 2.44$\pm$0.23 |
| J230546.2-331038 | 25.49$\pm$0.06 | 13.58$\pm$0.01 | 2.10$\pm$0.27 |
| J232513.3-302235 | 24.69$\pm$0.11 | 13.63$\pm$0.06 | 2.95$\pm$0.30 |
| J232900.6-321744 | 25.15$\pm$0.06 | 13.45$\pm$0.06 | 2.30$\pm$0.19 |
Figure 4. The $q_{\text{FIR}}$ parameter (see equation 1) as a function of redshift. The grey dashed line corresponds to the median $q_{\text{FIR}}$ for star-forming galaxies as defined by Ivison et al. (2010b), the grey shaded area represents the 2σ dispersion. Red and black shaded areas represent respectively the relation by Magnelli et al. (2015) and Delhaize et al. (2017). Stars are the 28 galaxies in our sample: (blue) the confirmed lensed objects, (yellow) the likely lensed objects, and (cyan) the uncertain objects. Arrows show the 3σ upper limits for the remaining undetected sources.

Figure 5. The $q_{\text{FIR}}$ parameter, computed using the FIR luminosity, as a function of the logarithm of the 1.4 GHz luminosity (not corrected for lens magnification). Circles are the Stacey et al. (2018) lensed quasars classified according to the origin of their radio emission: (red) jets, (green) star formation, and (blue) unknown. Squares are from Stacey et al. (2019). Arrows show the 3σ upper limits for the remaining undetected sources.
emission is unknown. They assumed a magnification factor of $\mu = 10^{+10}_{-3}$ for the majority of their sample, and the estimated median value of the total infrared luminosity amounts to $3.6^{+13}_{-4} \times 10^{11} L_\odot$.

Two additional sources are the gravitationally lensed radio-quiet quasars targeted by the LOFAR Two-metre Sky Survey (LoTSS) and detected by Herschel described in Stacey et al. (2019).

19 out of the 31 detected lensed quasars from Stacey et al. (2018) are located below the threshold of 1.8 and are mostly (with only one exception) classified as jet-dominated. For the remaining sources, only two quasars are confirmed to be star formation-dominated sources and are found to be above the 1.8 threshold within their uncertainties. The nature of the radio emission of the remaining one third of the sample (10 sources) is still uncertain. Only the 25% of their sample has $q_{\text{FIR}} < 1.8$ and lie in the same region of the jet-dominated quasars of Stacey et al. (2018), actually aligning onto their trend of $q_{\text{FIR}}$ with radio luminosity. Most relevantly, the majority of our sources lie ($\sim 90\%$) in the region where radio emission is dominated by star formation, thus complementing the radiospectroscopy adopted in Stacey et al. (2018) and actually extending to lower radio luminosities a consistent $q_{\text{FIR}}$ vs. radio luminosity relation.

Finally, our assumption that the FIR luminosity is not strongly affected by nearby objects entering the Herschel beam is reasonable. If not, the trend in Figure 5 should show a clear offset with respect to the confirmed lensed galaxies and/or with the points from Stacey et al. (2018, 2019). Another support to this assumption is given by the fact that our points are consistent within the uncertainties with the span of the $q_{\text{FIR}} - L_{1.4\text{GHz}}$ relation.

4 PHYSICAL INTERPRETATION

In the way of providing a physical interpretation, in Fig. 6 we compare the observed FIR-radio correlation from this work and from Stacey et al. (2018, 2019) to the in-situ galaxy formation scenario by Lapi et al. (2014, 2018) (see also Mancuso et al. 2017, Panyoni et al. 2019). This scenario envisages star formation and (super)massive black hole (BH) accretion in galaxies to be essentially in-situ and time-coordinated processes, triggered by the fast collapse of baryons in the host dark matter halos and subsequently controlled by self-regulated baryonic physics, in particular by energy/momentum feedback from SNe and from the central active nucleus.

The evolution of an individual massive galaxy (say the high-redshift star-forming progenitor of a present-day elliptical) predicted by the model consists of different stages (see Lapi et al. 2018, their Fig. 1 for a schematic illustration). Early on, the balance between cooling, infall, compaction and stellar feedback processes sets in a strong and dust-enshrouded star formation activity (SFR; several $10^2 M_\odot$ yr$^{-1}$), with a roughly constant behaviour in time (stellar mass increases almost linearly). Meanwhile, in the inner, gas-rich galaxy regions the central BH undergoes an exponential growth in Eddington-limited conditions. In this stage the system behaves as a bright IR/submm galaxy with an X-ray active nucleus. When the central BH has grown to a significant mass, its energy output becomes so large as to eject gas and dust from the host and eventually quench the star formation and reduce the accretion onto itself to sub-Eddington values. In this stage the system behaves as a powerful AGN with possible residual star formation. Thereafter, the stellar population evolves almost passively, and the system behaves as a red and dead massive quiescent galaxy; its further evolution in mass and size toward the present is mainly due to minor dry merger events.

In the early stages of the evolution when the central BH is still small and the nuclear power quite limited, the radio emission is mostly associated to the star formation in the host, implying modest $L_{1.4\text{GHz}}$ and standard values $q_{\text{FIR}} \approx 2.5$. Later on, when the BH mass has increased to substantial values, the radio emission from the nucleus progressively overwhelms that from the star formation, driving $q_{\text{FIR}}$ toward values appreciably smaller than 2.5. Values smaller even than 1.8 are obtained when jetted emission is produced, preferentially in the late-stage of the evolution: this is because extraction of rotational energy to drive jets is favoured in sub-Eddington conditions that sets in when the gaseous environment around the BH has been partially cleaned by the feedback from the nucleus itself (see above).

The typical model evolutionary track of a radio-loud AGN in the $q_{\text{FIR}}$ vs. radio luminosity diagram is illustrated by the black line with arrows in Fig. 6; the dark shaded area is the locus expected for such objects taking into account the relative contribution of sources with different masses, weighted by their statistics and timescales. For reference, the light shaded area refers to the typical $q_{\text{FIR}}$ parameter of a star-forming galaxies with negligible contribution from AGNs to the radio emission. The agreement of the model prediction with the data is pleasingly good, and testifies that the behaviour of the FIR-radio correlation is physically driven by the onset of jetted radio emission, and consistent with a co-evolution scenario between star formation and BH growth. A further, more detailed comparison between such a scenario and data will be pursued in a forthcoming paper, where we will estimate physical quantities (e.g., SFR, stellar mass, stellar ages, etc.) for the galaxy sample presented in this work via broadband spectral energy distribution fitting.

5 CONCLUSIONS

Our analysis exploited the FIR-selected, Herschel-ATLAS (HATLAS) candidate strongly-lensed galaxy sample by Negrello et al. (2017) to investigate the FIR-radio correlation out to redshift $z \sim 4$. Specifically:

- We cross-matched the Negrello et al. (2017) sample with the FIRST survey at 1.4 GHz and run dedicated follow-up with ATCA at 2.1 GHz, finding 11 and 16 matches, respectively; the addition of another source observed at $\sim 7$ GHz with the JVLA (analysed in detail by Nayyeri et al. 2017) led us to a sample of 28 candidate lensed dusty star-forming galaxies with a radio counterpart over the redshift range $1 \leq z \leq 4$.

- We derived the radio and the integrated FIR luminosities for the selected sample (uncorrected for lensing magnification), that feature radio luminosities in the range $1.9 \times 10^{24} \leq L_{1.4\text{GHz}} [\text{W Hz}^{-1}] \leq 1.8 \times 10^{26}$ and integrated FIR luminosity in the range $1.3 \times 10^{13} \leq L_{\text{FIR}} / L_\odot \leq 1.1 \times 10^{14}$.

- By taking advantage of the source brightness possibly enhanced by lensing magnification we identified a weak evolution with redshift out to $z \leq 4$ of the FIR-to-radio luminosity ratio $q_{\text{FIR}}$, consistent with previous determinations at lower redshift based on different selections.

- We found that the $q_{\text{FIR}}$ parameter as a function of the radio power $L_{1.4\text{GHz}}$ displays a clear decreasing trend, similarly to the lensed quasars selected in optical/radio by Stacey et al. (2018), yet covering a complementary region in the $q_{\text{FIR}} - L_{1.4\text{GHz}}$ diagram.

- We interpreted the behavior of the FIR-radio correlation according to an in-situ galaxy evolution scenario, as the result of the transition from an early dust-obscured star-forming phase (mainly
Figure 6. The FIR-radio correlation in terms of the $q_{\text{FIR}}$ vs. radio luminosity (uncorrected for lensing magnification). Data from this work (stars) and from Stacey et al. (2018, 2019). Circles: red for jetted source, green for star-forming galaxies and blue for uncertain ones) are compared with the prediction of the in-situ galaxy formation scenario by Lapi et al. (2014, 2018) for radio loud AGNs. Specifically, the dark grey area represent the locus of radio-loud AGNs and the light shaded area that for star-forming galaxies without a significant AGN contribution to the radio emission. The black line with arrows illustrates the typical evolution of an individual radio-loud AGN at $z \approx 2$. An average magnification ($\mu$) $\sim 10$ (as estimated by Stacey et al. 2018) has been applied to the model predictions for fair comparison with the data of gravitationally lensed sources.

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DATA AVAILABILITY

The data underlying this article are the following:

- The public catalogue of 80 candidate gravitationally lensed galaxies extracted from the full H-ATLAS survey, published by Negrello et al. (2017);
- The Herschel/SPIRE images at 250$\mu$m, produced from the H-ATLAS DR2 maps (https://www.h-atlas.org/public-data/download);
- The Australian Telescope Compact Array data products from the Australia Telescope Online Archive, publicly available at the following link: https://atoa.atnf.csiro.au/query.jsp, project code: C3215;
- The last version of the Very Large Array FIRST survey catalogue (2014 Dec 14, Helfand et al. 2015), accessible through VizieR: https://vizier.u-strasbg.fr/viz-bin/VizieR-3;
- The Very Large Array FIRST survey maps extracted from the cutout service available at the following link: https://third.ucllnl.org/cgi-bin/firstcutout;
- HST images taken from MAST: Barbara A. Mikulski Archive for Space Telescopes, https://mast.stsci.edu/.
- VIKING and UKIDSS-LAS cutouts, generated from https://alasky.u-strasbg.fr/hipsimage-services/hips2fits.
- ALMA images available in the ALMA Science Archive,
