The far-infrared-radio correlation in galaxies

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Abstract

The tightness and universality of the far-infrared (FIR) to radio continuum (RC) correlation is still not completely understood. This correlation is followed by all star-forming galaxies not dominated by an Active Galactic Nucleus, both globally as well as locally within the disks. There is a general consensus that star formation (SF) is the ultimate driver of the relation, in the sense that the bulk of dust emission in the FIR is powered by young stars ending their lives as supernovae which are the main sites of Cosmic Ray (CR) acceleration. Although this simplistic view is correct, it neglects many of the additional parameters that affect the correlation. Thus, a detailed understanding is still missing which is crucial in order to correctly use the RC emission as a tracer of recent SF with the important advantage not to be affected by extinction. Furthermore, a detailed understanding of the correlation will lead to a deeper understanding of dust heating, the interstellar medium (ISM) and propagation of CRs.

The capabilities of the SKA are needed to make progress in our understanding of the correlation. In particular, they will allow us to (i) extend the study of the correlation to low-luminosity dwarf galaxies which are expected not to follow the correlation so well, (ii) extend the correlation to high-z objects and test whether the correlation is still fulfilled, and (iii) study the properties of CR propagation in galactic halos via changes in the spectral index in order to be able to compare the relative relevance of propagation, escape and energy losses.

1 Physical basis and relevance of the correlation

The tight correlation between the radio continuum (RC) and the far-infrared (FIR) emission of galaxies [13, 8] holds over 5 orders of magnitude in luminosity with a very low scatter of about 0.26 dex [42] and is followed by basically all star-forming galaxies unless they have a radio-loud Active Galactic Nucleus (AGN). Discovered from data at 60 μm and 100 μm from the IRAS satellite, it has since afterwards also been tested with data from the satellites Spitzer (24 μm, 70 μm, and 160μm) and Herschel (70 μm, 100 μm, 160μm, and 250μm).

There is a general agreement that the basic underlying driver of this correlation is massive star formation (SF). Massive stars are the main heating sources of the interstellar dust, both locally in HII regions and also, mainly through their non-ionizing UV radiation [43], of the diffuse dust distributed in the ISM in galaxies. Massive stars are at the same time responsible for the radio emission in two ways: The ionizing photons that they emit produce the thermal (free-free) radio emission in HII regions and they end their lives as supernovae (SN) whose remnants accelerate Cosmic Rays Electrons (CREs) emitting radio synchrotron emission on their way through the interstellar magnetic field.

However, although this basic relation is clear, the step from massive SF to the RC emission on one side and FIR emission on the other side is not completely direct but involves instead a considerable number of parameters. For the FIR emission the main additional parameter is the dust opacity in a galactic disk which can vary from well below one in dwarf galaxies to completely optically thick as in dust-enshrouded starburst galaxies. The RC emission is based on even more complex processes. First of all, it consists of two radio components, each of which is based on a completely different process: free-free or bremsstrahlung emission from thermal electrons in HII regions (the thermal radio emission) and synchrotron emission from CREs. Generally, in the GHz observing range, the synchrotron emission is dominant with a typical thermal-to-total radio flux ratio of 10% [6]. Synchrotron radiation is emitted from CREs propagating away from their acceleration sites (SN remnants), suffering at the same time energy losses and emitting synchrotron radiation. The energy losses are predominately inverse Compton and synchrotron losses in spiral galaxies, but in starburst galaxies also bremsstrahlung, ionization and adiabatic energy losses can become important [38, 28]. Therefore a large number of parameters come into play when describing the synchrotron emission of a galaxy, the most important ones being the magnetic field, energy density of the radiation field, gas density, diffusion and convection velocities and the halos size. Considering this complex relation between the origin (massive stars) and the results (FIR and RC emission) it is a priori hard to understand how the FIR-radio correlation can be so tight and universal.

The FIR-radio correlation has had, apart from challenging our understanding of the processes of dust heating and CR propagation, two important applications. First of all, the relation of the RC emission with massive SF that it implies show that the RC emission can be used as a SF tracer [6, 15]. The chapter of Torres et al. (this book) deals with the topic of RC emission as SF tracer in more detail. Other commonly used SF tracers, as the Hα or UV emission have the disadvantage that they are extincted by dust and that the correction for dust-extinction is difficult and results in a considerable uncertainty. The dust emission in the mid-infrared (typically taken at 24 or 70 μm) which is also frequently used as a SF tracer on its own or in combination with Hα or UV (e.g. [18, 4]) is not affected by dust extinction. However, these observations need to be done from space and come therefore only from satellite missions (Spitzer, Herschel, WISE) and have a limited spatial resolution of $6''$ to $36''$. The RC emission avoids both disadvantages since it is not affected by dust and interferometers from the earth surface can obtain sub-arcsec resolutions. Both properties are particularly important when observing distant galaxies and will be crucial for studies of the cosmic star formation history once sensitive observations with SKA will be possible. A second application of the FIR-radio correlation has been the use of the radio-submillimeter ratio as a photometric redshift indicator [3]. This relation could be derived based on the tightness of the FIR-radio correlation.

Thus, a deep understanding of the detailed physical processes that drive the FIR-radio correlation is crucial not only for our knowledge of the ISM but also in order to be able to apply the RC emission as a SF tracer and the radio-submillimeter ratio as a redshift indicator. Both applications are of particular relevance for studies of the high-redshift universe where unknown extinction corrections can lead to enormous errors.

2 Observations of the FIR-radio correlation

The FIR-radio correlation has been tested for many galaxy samples, and found to hold for all galaxies irrespective of their morphological type or star formation rate (SFR). The only exception are galaxies where CRE acceleration outside SN remnants (SNRs) takes place, as is the case in galaxies with a radio-loud Active Galactic Nucleus (AGN), galaxies in clusters where interaction with the Intragroup Medium might produce shocks accelerating CRs [40, 25] or between interacting galaxies that collided face-on [30]. The correlation is roughly linear and holds over 5 orders of magnitude [42]. At low luminosities, the situation is less clear. Some studies indicate that the correlation holds also for dwarf galaxies [5, 31], whereas in the largest sample studied up to date of 26 dwarf galaxies, Kitchener et al. [17] find a lack of RC emission compared to brighter objects. The discrepancy is probably due to the faintness of the objects which lead to a high fraction of upper limits in the samples [5] and the need to stack data [31].

Apart from samples of local galaxies, the FIR-radio correlation has also been tested for high-z galaxies. So far, no clear indications for a deviation at high redshifts have been found. Several studies confirm the validity of the FIR-radio correlation out to redshifts of about 1-2 [12, 1, 32, 33] with only a few giving tentative evidence for a deviation (lower radio emission) at higher z (z $\sim$ 3-6) [26, 35]. However, due to their faintness, reliable conclusions for these high redshift galaxies are difficult.

The correlation does not only hold globally, but also locally within galaxies. It has been shown to hold down to about 20-50 pc in the Milky Way [41] and the Large Magellanic Cloud [16], a scale which is dominated by thermal radio emission from HII regions. At larger scales, where synchrotron emission becomes dominant, the scale where the correlation breaks down is expected to depend on the dust opacity and, most importantly, on the diffusion length of

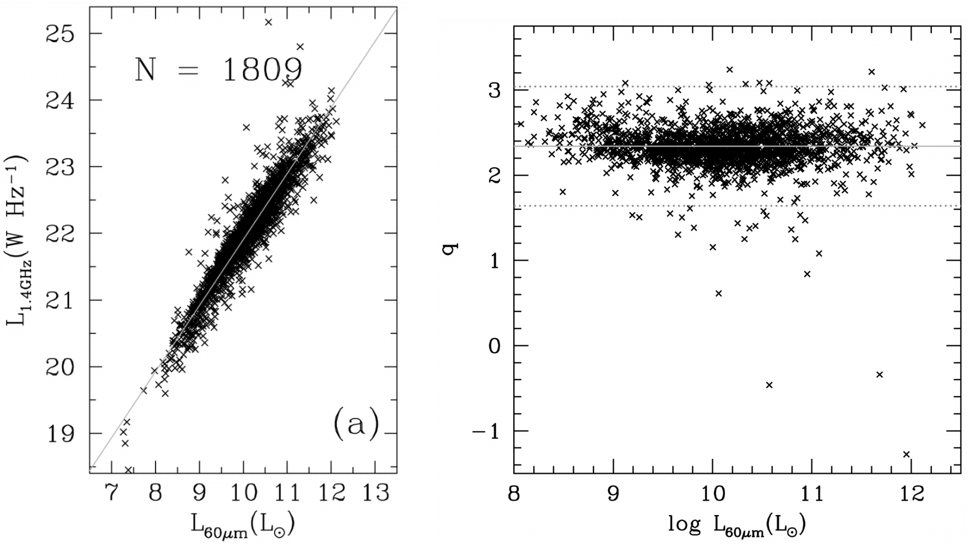

Figure 1: Example of the FIR-radio correlation for a sample of 1809 galaxies with $S_{60\mu\text{m}} > 2$ Jy, taken from Yun et al. [42]. **Left:** The radio luminosity at 1.4 GHz vs. the luminosity at 60 μm from IRAS data. The solid line corresponds to a linear relation with a constant offset. **Right:** Distribution of q-values ($q = \log\left(\frac{FIR}{3.75\times10^{12}\text{Wm}^{-2}}\right) - \log\left(\frac{S_{1.4\text{GHz}}}{\text{Wm}^{-2}\text{Hz}^{-1}}\right)$, with $FIR = 1.26\times10^{-14}(2.58S_{60\mu\text{m}} + S_{100\mu\text{m}})$, where $S_{1.4\text{GHz}}$ is the observed 1.4 GHz flux density and $S_{60\mu\text{m}}$ and $S_{100\mu\text{m}}$ denoting the IRAS 60 and 100 μm band flux densities in units of Jy), plotted as a function of the IRAS 60μm luminosity. The solid line marks the average value of $q = 2.34$, while the dotted lines delineate a limit of 5 × the standard deviation. The radio-excess objects (below the line) are likely to be dominated by an AGN.

CREs in galactic disks. Since the arrival of Spitzer and Herschel data, studies of the local FIR-radio have been possible at scales on the order of $10''$. Murphy et al. [22, 23, 24] has shown for galaxies from the Spitzer Infrared Nearby Galaxy Survey (SINGS) that the RC emission agrees very well with a spatially smoothed version of the FIR emission showing that CRE propagation away from the sites of acceleration is important. Detailed analysis of the spatial scales with a wavelet analysis have shown that the correlation holds down to scales of between several hundred parsec to 1 kpc ($<$ 0.4 kpc for M33 [37], 0.7 kpc for M51 [11], $\sim$ 1kpc for M31 [37] and $\sim$ 2 kpc for NGC 6946 [36]). The different scales might be related to properties of the magnetic field determining the CR propagation [37].

3 Models

The tightness and the universality of the correlation has inspired many researchers to model the correlation in order to draw conclusions about processes taking place in the ISM. In general, models agree that the fundamental reason for the existence of the correlation is massive SF that is ultimately responsible for both the dust heating as well as for CR acceleration and thus synchrotron emission.

A crucial question for our understanding of the FIR-radio correlation is whether galaxies are optically thick ("calorimeters") to their UV radiation and to the energy of their CRE, or optically thin. In the calorimeter case it can be shown that the massive SFR is basically the only parameter, and that the dust opacity and the magnetic field play only a very minor role [39, 19]. In this case the tightness of the correlation can thus be easily understood. In the optically thin case, models relating dust opacity and the CRE escape length [13] or the gas density and magnetic field [27] have been proposed.

A calorimeter situation is certainly present in dense starburst galaxies where the energy loss time-scale of CREs becomes very short [38]. However, in this regime both gas density, the energy density of the radiation field and most likely the magnetic field is much increased [38, 28]. This has several consequences: (i) Secondary electrons and positrons, which are the result of the decay of pions that were produced in collisions from CR protons with the interstellar gas protons, contribute considerably to the RC emission. (ii) Energy losses due to the inverse Compton effect, ionization losses and bremsstrahlung dominate over the synchrotron losses, producing a "synchrotron dimming". Lacki et al. [28] present a model taking these effects into account. They show that all these effects are proportional to the gas surface density and that for a certain choice of the parameters, the different effects compensate and produce a rather constant FIR-to-radio ratio.

On the other side of the luminosity spectrum, dwarf galaxies are certainly no calorimeters because they are characterized by low dust opacities and CR escape leading to a suppression of both the FIR and the RC emission compared to other SF tracers [2]. To which extent the decrease of both emissions "conspires" [2] to preserve the FIR-radio correlation is unclear. The model of Lacki et al. [29] predicts a break-down of the correlation for low surface brightness dwarfs who are expected to be radio synchrotron weak. A firm observational confirmation of this prediction is still missing, partly due to the difficulty to separate synchrotron and thermal radio emission.

At which luminosities the transition between optically thin and optically thick takes place exactly is still uncertain, and in particular the question of whether normal spiral galaxies are calorimeters or not. The only way to answer this question is via radio spectral index maps of the galactic halos because a steepening of the spectral index away from the disk is a unique sign that energy losses dominate over escape [20]. So far, the sensitivity of the radio data only allows this measurement in bright starburst galaxies and has generally shown a steepening of the spectral index [9, 10, 14]. Measurement for normal spiral galaxies will only be possible with the SKA.

All these models have been developed for nearby galaxies. From theoretical considerations, the FIR-radio correlation is expected to break down at high redshifts. The main reason is the increase of the energy density of the Cosmic Microwave Background which leads to an increase of inverse Compton losses compared to synchrotron losses and therefore to an increasing radio synchrotron dimming [26, 29]. The break-down of the correlation is expected to occur first in galaxies with a moderate SFR (at $z \sim 2$) and later in starburst galaxies (at $z \sim 10-20$) if the general morphologies of the galaxies are similar to local ones [29].

4 The need for the SKA

In order to make progress in our understanding of the correlation, observational data of higher sensitivity are required which can only be provided by the SKA. Already in the first phase, SKA1-mid will provide an improvement of a factor of 5 in sensitivity and at the same time an improvement of a factor of ~ 5 in spatial resolution compared to the JVLA which is the most powerful instrument at present. The large band width of 500 - 700 MHz in the GHz range making an in-band spectral index determination possible is an additional feature that will help to solve the open questions. making galaxy surveys very efficient. At full performance, the SKA is expected to improve a further factor 10-20 in sensitivity in the GHz frequency range. The data that can be acquired with the SKA1 (and later SKA) will help us to answer the following questions:

- Does the FIR-RC correlation hold in dwarf galaxies with the same low scatter as in spirals and starbursts? If yes, this would require a fine-tuning between parameters relating the dust emission and the CR escape. So far, only a modest amount of RC data for dwarf galaxies is available and indicate a lack of RC emission compared to the FIR. Data for a larger sample are needed in order to further quantify this trend and draw statistical conclusions. The largest sample of 26 galaxies observed by Kitchener et al. [17] contains galaxies out to a distance of up to 10 Mpc with total SFRs down to 10^{-3} to $10^{-4} M_\odot$ yr^{-1}. The improvement in sensitivity of a factor of 5 of SKA-mid compared to the JVLA will allow us to observe similar galaxies as in this survey with the same observing time out to about twice the distance with about twice the linear spatial resolution. This will allow us to obtain high-quality data for a sample of about 10 times more galaxies, i.e. hundreds of objects, in the same observing time.

- What are the properties of radio halos of galaxies? Are they loss-dominated or escape-dominated? We need to know this in order to be able to understand the FIR-to-radio correlation and in particular, find out whether there is a direct relation between RC emission and the SFR which is assumed when using the RC emission as a SF tracer. Radio halos are intrinsically faint and extended which makes their observation difficult. They are most likely powered by star formation [9, 10] so that a higher SFR can power larger and brighter halos. With the current instruments, radio halos have only been detected in a handful of starburst galaxies, with NGC 253 [14] (SFR of 5 $M_\odot$ yr^{-1}) being one of the least luminous objects observed. The large field of view, high sensitivity, high resolution (necessary to resolve also smaller halos) and multi-frequency capacity of SKA1 will allow such studies in galaxies similar to the Milky Way (SFR ≈ 1 $M_\odot$ yr^{-1}) in a few hours.

- Does the FIR-radio correlation hold for galaxies at high redshift? The correlation is expected to break down at some point and the precise value of the redshift where this happens will allow us to draw conclusions about the other energy losses that CRE suffer apart from invers-Compton losses. Furthermore, we need to know the range of validity of the FIR-radio correlation with redshift in order to limit the range where the RC can be used as a SF indicator. Surveys up to date, like VLA-Cosmos [34] which achieved in

275 hours of observations a rms of 17 μJy at a resolution of $2.5''$ have been able to detect galaxies out to $z \approx 1-2$ with its field of 2 deg^2. The instrument SKA1-mid is able to observe in the same time the same area down to a 25 times lower rms (0.7 μJy) at a high spatial resolution ($\sim 0.2''$), which is important to avoid confusion. Following the estimation of Murphy et al. [26] (his Fig. 3), adapted to the sensitivity of SKA1-mid, we find that this instrument will be able to detect Luminous Infrared Galaxies (LIRGs, $L \geq 10^{11}$ $L_\odot$) out to $z \sim 1.5$ and Ultraluminous Infrared Galaxies (ULIRGs, $L \geq 10^{12}$ $L_\odot$) out to $z \sim 3$. With the factor 10 improvement expected in the future, the final SKA survey instrument will be able to detect ULIRGs at all redshifts and LIRGS out to $z \sim 3$.

5 Summary and conclusions

Observations with the SKA will allow to answer open questions about the FIR-radio correlation that are beyond the reach of present instruments. They will improve our knowledge about the CR propagation and properties of the ISM (magnetic field, gas density, radiation field) and will allow us to reliably calibrate the RC emission as an extinction-free SF indicator. Such an extinction-free SF indicator is highly needed, especially when studying the high-z universe which will be an increasingly accessible topic in the future.

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