Predictions of radio counts of star forming galaxies for SKA precursors

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Abstract. We extended recent semi-analytical galaxy formation models, that fitted the far-infrared (FIR) to millimeter wave luminosity functions and ultraviolet (UV) luminosity functions up to high redshifts, in order to take into account additional UV data and Hα luminosity functions. The latters are tracers of star formation in evolved galaxies at low redshifts. Using the relations between star formation rate (SFR) and radio (synchrotron and free-free) emission, we obtained predictions for the counts of star-forming galaxies down to sub-nJy fluxes. These will be very useful for the new generation of radio telescopes, thanks to which it will be possible to investigate smaller and smaller radio fluxes (down to nJy), making the detection of little SFR possible.

1. Introduction

It is now well proven, thanks to the recent surveys carried out by Spitzer [1], Herschel [2], SCUBA[3] and South Pole Telescope (SPT) [4], that the infrared (IR) luminosity of galaxies at high-z is strongly related to ongoing star formation. However the newly born stars light is not always completely absorbed and re-emitted in the IR: this is the case of the earliest phase of galaxy evolution, when the interstellar medium is not extremely metal enriched, making the dust absorption only marginal. Also irregular and spiral galaxies at moderate to low-z, where the optical depth of the medium is little enough to let some UV radiation to survive, do not shine exclusively in the IR. The estimation of the star formation rate (SFR) is then possible thanks to a combination of IR and UV photometry, suffering from limitations in both wavebands.

Another powerful tracer of the SFR, independent of dust absorption, is the radio continuum emission. Since many years it has been established a tight relation between low frequency radio (synchrotron) and IR luminosity, even if its physical basis are not totally clear yet [5]. In fact the many physical processes contributing to this emission (propagation of relativistic electrons, strength and structure of the magnetic field, size and composition of dust grains) do not guarantee the extension of the relation up to redshift/luminosity ranges where there are not enough observational data available to test it properly.
The radio emission of star forming galaxies is however due also to a second process: the free free emission from relativistic electrons, which is directly proportional to the ionising photon rate of young, massive stars. It shows up at rest frame frequencies of tens of GHz, offering a relatively clean way to quantify the current star formation activity in galaxies. Some contamination, in this case, can derive from anomalous dust emission occurring at similar frequencies, thought to be due to spinning dust grains: there is however no proof that the contribution of this component can seriously affect the globally integrated measurements [6]. As a consequence high frequency radio observations can provide a very powerful tool to measure the star formation history of the Universe.

Padovani[7] demonstrated that at GHz frequencies, the counts below 100-200 µJy are dominated by star-forming galaxies: unfortunately this limit is not covered by the ongoing surveys, but it will be easily reached by the new generation radio telescopes.

2. The model
A detailed physical model for the evolution of the UV luminosity functions, hence of the cosmic SFR at high-z, has been worked out by Cai[8] in the framework of the scenario proposed by Granato[9] and further elaborated by Lapi[10, 11]and Cai[12]. In the latter the authors carried out a complete investigation of the evolution of the IR luminosity functions based on a “hybrid” approach, that reflects the observed dichotomy in the ages of stellar populations of early-type galaxies on one side and late-type galaxies on the other (cf. Fig. 10 in [13]). Early-type galaxies and massive bulges of Sa type galaxies are composed of relatively old stellar populations with mass-weighted ages \( \gtrsim 8–9 \) Gyr (corresponding to formation redshifts \( z \gtrsim 1–1.5 \)), while the disk components of spirals and the irregular galaxies are characterized by significantly younger stellar populations. Thus the progenitors of early-type galaxies, referred to as proto-spheroidal galaxies or protospheroids, are the dominant star-forming population at \( z \gtrsim 1.5 \) while IR galaxies at \( z \lesssim 1.5 \) are mostly late-type “cold” (normal) and “warm” (starburst) galaxies.

The model accurately fits a broad variety of data: multi-frequency and multi-epoch luminosity functions of galaxies and Active Galactic Nuclei (AGN), redshift distributions, number counts (total and per redshift bin). It also accounts for the recently determined counts and redshift distributions of strongly lensed galaxies detected by the South Pole Telescope (SPT)[14].

Although the total (8–1000 µm) IR luminosity (\( L_{IR} \)) is a good proxy of the SFR when the dust heating is dominated by young stars and the effective optical/UV optical depth is high, in disks of normal galaxies the IR luminosity is the sum of a “warm” component heated by young stars and of a “cold” (or “cirrus”) component, heated by the general radiation field that may be dominated by older stars. Obviously only the first component is a tracer of the SFR. This issue was investigated by Clemens[16]. We adopt the relation between SFR and \( L_{IR} \) derived by these authors.

Galaxies with low SFRs are also found to have low dust opacity, making the SFR derived from \( L_{IR} \) underestimated even by large factors. It must then be complemented using optical/UV SFR indicators: we supplemented them with a parametric phenomenological backward model, considering both the UV and the H\( \alpha \) data (see Fig. 1).

For modelling the UV (\( \lambda = 1500 \AA \)) luminosity functions of late-type galaxies we adopted the same functional form used by Cai[12] in the IR. We used a simple pure luminosity evolution model (\( L^*(z) = L_0^*(1 + z)^{\alpha L} \) up to \( z = 1 \)), that turned out to provide a sufficiently good description of the data. For proto-spheroidal galaxies we kept instead the Cai[8] physical model.

3. Calibration of the relation between radio emission and SFR
For extending the model to the radio frequencies we used the calibration of the relation between the SFR and the synchrotron emission calculated by Murphy[17]. In order to take into account electron ageing effects we adopted a steepening by \( \Delta \alpha = 0.5 \) above a break frequency of 20 GHz,
**Figure 1.** SFR functions at several redshifts. The blue lines show the SFR functions derived from the UV luminosity functions given by the phenomenological model for late-type galaxies with and without correcting the observed luminosities for extinction (dashed and thin solid lines, respectively). The dot-dashed orange lines show, only at $z \geq 1.5$, the contributions given by the physical model for proto-spheroids with a minimum halo mass $M_{\text{min}} = 10^{8.5} M_\odot$. The thick black lines show the sum of the contributions from late-type galaxies, after the extinction correction, and of proto-spheroids.

**Figure 2.** Euclidean normalized differential counts at 1.4 GHz compared with model predictions.

**Figure 3.** Right panel: predicted redshift distributions for 1.4 GHz surveys down to 50 and 5 $\mu$Jy.
making the SFR-synchrotron luminosity relation to be:

\[ L_{\text{sync}} \simeq 1.9 \times 10^{28} \left( \frac{\text{SFR}}{M_\odot \text{yr}^{-1}} \right) \left( \frac{\nu}{\text{GHz}} \right)^{-0.85} \left[ 1 + \left( \frac{\nu}{20 \text{GHz}} \right)^{0.5} \right]^{-1} \text{erg s}^{-1} \text{Hz}^{-1}. \] (1)

This relation was checked with the available sub-mJy 1.4 GHz observational counts (Fig. 2), showing a good match.

A relation between SFR and free-free emission was derived by Murphy[6]. We reformulated it as:

\[ L_{\text{ff}} = 3.75 \times 10^{26} \left( \frac{\text{SFR}}{M_\odot \text{yr}^{-1}} \right) \left( \frac{T}{10^4 \text{K}} \right)^{-0.5} \times g(\nu, T) \times \exp \left( -\frac{h\nu}{kT} \right) \text{erg s}^{-1} \text{Hz}^{-1} \] (2)

where \( T \) is the temperature of the emitting plasma and \( g(\nu, T) \) is the Gaunt factor for which we adopt a more accurate approximation than that generally used [18]. The coefficient of eq. (2) was computed requiring that this equation equals that by Murphy[6] for \( \nu = 33 \text{ GHz} \) (the frequency at which the relation was calibrated).

To test this relation we have used SPT observations of dusty galaxies at 95 GHz [14]. In fact we expect that, at this frequency, the flux densities of local galaxies not hosting a radio loud AGN are dominated by free-free emission. To estimate the 95 GHz counts of dusty galaxies Mocanu adopted a statistical approach, that is endowed with large uncertainties and may strongly overestimate the counts of dusty galaxies. We have then re-estimated the counts checking the Spectral Energy Distribution (SED) of each 95 GHz source brighter than the 95% completeness limit of 12.6 mJy, collecting all the photometric data available in the literature. We found that only 4 sources are indeed dusty galaxies, in good agreement with the modelled counts.

4. Predictions for new generation radio telescopes
The new generation radio telescopes include the precursors for the SKA, that are starting to run in these years. The main surveys predicted to be performed in the continuum are EMU (Evolutionary Map of the Universe), which will use the ASKAP (Australian SKA Pathfinder) telescope to make a deep (\( \sim10\mu\text{Jy rms} \)) survey at 1.4 GHz, covering the entire Southern Sky, and MIGHTEE (MeerKAT International GigaHertz Tiered Exploration) on the MeerKAT telescope in South Africa, which will have \( \sim1\mu\text{Jy rms} \) at 1.4 GHz [15].

We performed predictions for both the number counts and the redshift distributions (Figs. 2 and 3). In Fig. 2 the dashed brown line shows the best fit model for radio AGNs by Massardi[19]. The other dashed lines show the contributions of the star-forming populations considered in this paper. The two triple-dot dashed lines show the total synchrotron and free-free emissions from all the populations. We indicated with solid vertical lines the 5\( \sigma \) limit for both the predicted surveys (in blue the flux limit for EMU, in salmon the one for MIGHTEE). According to the model we can see that the main contributors to the “hump” at tens of \( \mu\text{Jy levels are late-type galaxies at } z \approx 1–1.5. \) Higher \( z \) proto-spheroidal galaxies become increasingly important at lower flux densities, down to a few hundred nJy’s. As a result, it’s clear that these new facilities will help to fill the gap between the limit reached by the current observational data and the fluxes where the contribution of star forming galaxies starts to be dominant.

The redshift distributions (Fig. 3), obtained for the 5\( \sigma \) flux density limits of EMU and Mightee (right and left side, respectively), show that the fraction of galaxies increases with decreasing flux density, in particular with MIGHTEE it will be possible to detect a sufficient amount of galaxies up to \( z=8 \). The tail of the distribution is moreover dominated by strongly lensed galaxies (those with magnification \( \mu_{\text{min}}=2 \)), that could be easily distinguished from the other populations if their redshift is accurately estimated. Unfortunately it’s not so easy to determine the redshifts of such objects, and we must look at some synergies with new generation telescopes, such as JWST [20], to have a reliable estimation.
5. Conclusions
The SKA precursors surveys can provide a much wider coverage of the SFR–z plane than UV and far-IR/sub-mm surveys. We have worked out detailed predictions of the counts and redshift distributions at the fluxes that can be reached by EMU and MIGHTEE surveys, distinguishing the contributions of the different populations of star-forming galaxies. To work out such predictions we used the models by Cai[12, 8], that accurately reproduce the available determinations of the epoch-dependent SFR function from both UV and far-IR/sub-mm surveys. We combined those with the relation between SFR and radio (synchrotron and free-free) emission, obtaining an extension of the model to radio frequencies. Since the Cai models did not include the contribution to the SFR of moderate to low redshift late-type and starburst galaxies, we took into account further information from Hα surveys and from additional UV data in order to be as complete as possible. The relation between SFR and synchrotron emission has been checked exploiting the deepest 1.4 GHz counts, while the relation between SFR and free-free emission has been tested using the 95 GHz South Pole Telescope counts of dusty galaxies.

With this approach we have shown that the SKA precursors will start to address a flux limit region unreachable with the current radio facilities, allowing us to have a more complete information, not affected by dust extinction, on galaxy SFRs. A more detailed discussion will be provided in a forthcoming paper [21].

Acknowledgements
We acknowledge financial support from ASI/INAF Agreement 2014-024-R.0 for the Planck LFI activity of Phase E2 and from PRIN INAF 2012, project “Looking into the dust-obscured phase of galaxy formation through cosmic zoom lenses in the Herschel Astrophysical Large Area Survey”.

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