Dwarf Galaxies: From the Deep Universe to the Present
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Stellar feedback in dwarf irregular galaxies with radio continuum observations

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Abstract. Low-mass dwarf irregular galaxies are subject to outflows, in which cosmic rays may play a very important role; they can be traced via their electron component, the cosmic ray electrons (CRe), in the radio continuum as non-thermal synchrotron emission. With the advent of sensitive low-frequency observations, such as with the Low-Frequency Array (LOFAR), we can trace CRe far away from star formation sites. Together with GHz-observations, such as with the Very Large Array (VLA), we can study spatially resolved radio continuum spectra at matched angular resolution and sensitivity. Here, we present results from our 6-GHz VLA survey of 40 nearby dwarf galaxies and our LOFAR study of the nearby starburst dwarf irregular galaxy IC 10. We explore the relation of RC emission with star formation tracers and study in IC 10 the nature of a low-frequency radio halo, which we find to be the result of a galactic wind.

Keywords. cosmic rays, galaxies: magnetic fields, radio continuum: galaxies

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1. Introduction

Radio continuum (RC) emission in galaxies holds the potential to be an extinction-free star-formation tracer, which is accessible with ground-based observations. This is supported not only by the well known correlation between RC and far-infrared (FIR) emission (e.g. Yun, Reddy & Condon 2001), but also by relations to other star-formation tracers such as far-UV (FUV) and mid-infrared (MIR) emission (Heesen *et al.* 2014; Tabatabaei *et al.* 2017). The correlation is tight, with a scatter of only 0.2 dex (50 per cent) for integrated quantities, and holds locally at 1-kpc scale, although with a larger scatter. Given the complex physics of RC emission in galaxies, the mere existence of a relation between RC luminosity and star-formation rate (SFR) is remarkable.

Dwarf galaxies, with their episodic star formation, low metallicities and thus potentially varying initial mass function, and their proneness to outflows offer a stringent test of the RC–SFR relation. Dwarf galaxies fall on the RC–FIR correlation (Bell 2003), which has been explained by 'conspiracy' between escape of dust-heating UV-photons and cosmic ray electrons (CRe); at a typical frequency of 6 GHz the latter are responsible via synchrotron emission for approximately half of the RC emission, the remainder coming from thermal free–free emission. In this brief contribution, we present a summary of our

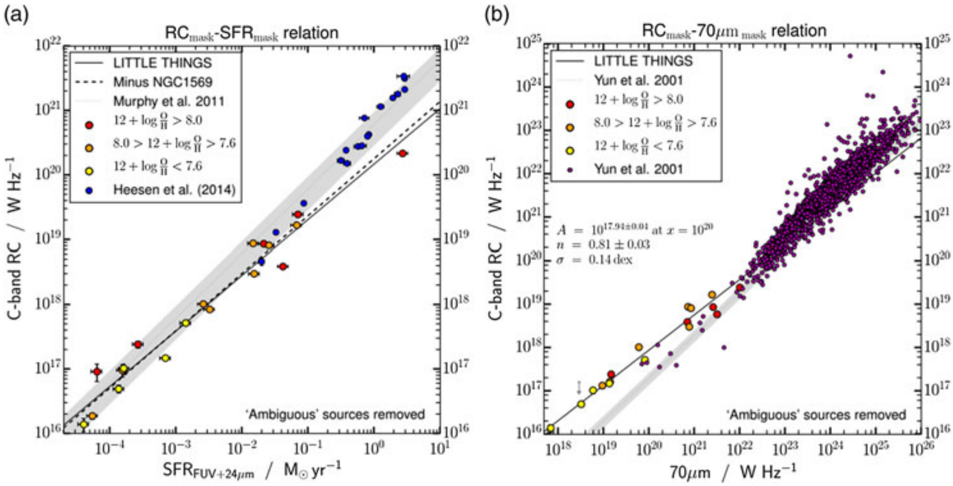

Figure 1. Comparison of the RC–SFR relation (a) and the RC–FIR correlation (b) in LITTLE THINGS dwarf galaxies. The dwarf galaxies (red and yellow data points) are in good agreement with the RC–SFR relation from Murphy *et al.* (2011) as indicated by the grey-shaded area in panel (a), just as the more massive late-type spiral galaxies (blue data points). However, they deviate from the RC–FIR correlation as shown by the grey-shaded area in panel (b), where the measured RC emission is too bright in comparison to the FIR emission.

recent work exploring the RC–SFR relation in dwarf galaxies, while also searching for radio haloes in order to directly trace the consequence of stellar feedback in the form of galactic outflows.

2. Radio continuum survey of LITTLE THINGS dwarf galaxies

We have observed 40 nearby dwarf galaxies from the LITTLE THINGS (Local Irregulars That Trace Luminosity Extremes, The H I Nearby Galaxy Survey; Hunter *et al.* 2012) survey with the Very Large Array (VLA) at 6 GHz (4–8 GHz) in C-configuration. We reached noise levels of 3–15 μJy beam^{-1} at 3–8 arcsec resolution, which allows us to carry out a reliable separation of unresolved background sources from intrinsic RC emission from the galaxies, something that has hampered previous studies with single-dish telescopes. We carefully study the RC emission with a mask in order to maximise the signal-to-noise ratio (see Hindson *et al.* 2018), for details.

We could show that, while dwarf galaxies fulfill the RC–SFR relation just as the more massive late-type spiral galaxies do, they deviate from the RC–FIR correlation being more radio bright than suggested by the FIR emission (Fig. 1). This shows that the FIR emission is not a reliable SF tracer in dwarf galaxies since they are low in dust content and so the UV-photons can escape. On the other hand, these same photons contribute to the hybrid SF tracer if FUV emission is included, so that they are providing still reliable SFRs even in these virtually dust-free systems.

On the other hand, closer inspection of the RC–SFR relation shows that the RC luminosities have the tendency to fall slightly below the relation defined by larger, spiral galaxies. We could show that this is related to the suppression of the non-thermal emission. There may be two reasons why the emission is suppressed: (i) weak magnetic fields or (ii) escape of CRe. The magnetic field strength as calculated from energy equipartition is averaged over the entire galaxy, with 5–8 μG slightly lower than in spiral galaxies. However, when spatially resolved, we find magnetic field strengths of up to 50 μG, showing that magnetic fields can be quite strong locally. This suggests that on the whole escape

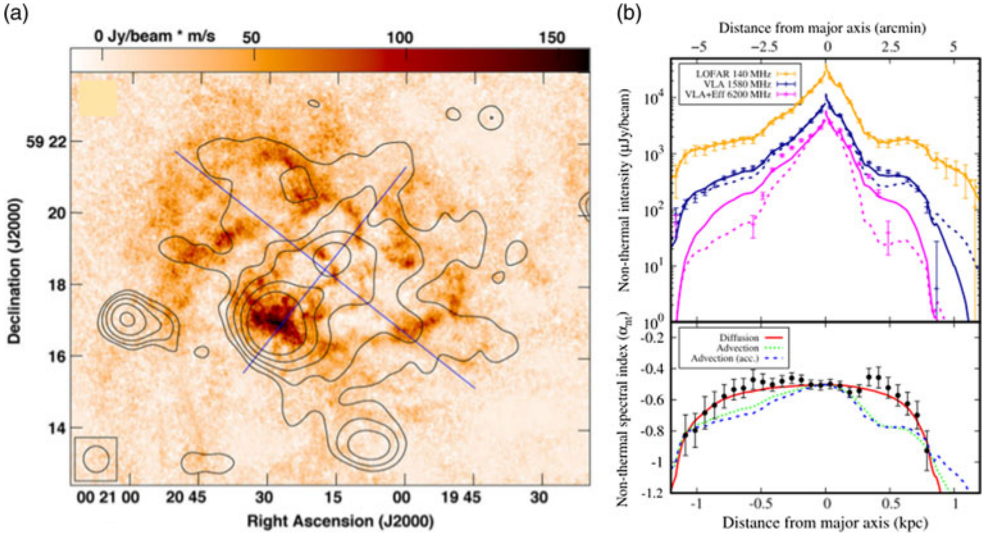

Figure 2. (a) 140-MHz RC emission in IC 10 at 44 arsec resolution overlaid on H I emission from the LITTLE THINGS survey. Contours start at 3σ and increase by powers of 2. Cyan lines show the position of the major and minor axes of the RC emission; note that the shorter line is actually the major axis, showing the extent of emission along the minor axis indicating the presence of a radio halo. (b) Minor axes RC profiles at different frequencies and spectral indices. Lines show the best-fitting cosmic ray transport models as fitted to the data.

of CRe, rather than weak magnetic fields, is behind the deficiency of the non-thermal RC emission. This can be explored further by studying the distribution of extra-planar RC emission in the form of radio haloes.

3. The low-frequency radio halo of the starburst dwarf galaxy IC 10

We hence proceeded to observe the nearby starburst dwarf irregular galaxy IC 10 with LOFAR at 140 MHz (115–178 MHz). We imaged the data at low angular resolution of 44 arcsec in order to improve the detectability of weak, diffuse emission (Heesen *et al.* 2018a). Our results show the existence of a radio halo, which manifests itself as a second component in the minor axis profiles of the RC emission (Fig. 2). IC 10 is moderately inclined ($i = 47^\circ$), but we could show that an intrinsic scale height of 0.5 kpc is required in order to explain the minor axes profiles. This scale height is comparable to the size of the galaxy, so one can say that the galaxy possesses indeed a radio halo.

The minor axes intensity profiles were fitted with cosmic-ray transport models, where we explored both models for pure advection and diffusion. While a diffusion model fits formally best, we actually prefer an advection model as expected for a galactic wind. The moderate inclination angle makes a distinction difficult on a formal basis. If we allow for an accelerating wind, the advection speed rises from $\sim 20\ \mathrm{km\,s^{-1}}$ in the galactic midplane to exceed the escape velocity of $50\ \mathrm{km\,s^{-1}}$ within 1 kpc height. Such a model can also explain the magnetic field, cosmic rays, atomic and ionised medium are in approximate energy equipartition in the disc as well as in the halo. Such an outcome allows the cosmic rays to play an important role when launching winds, which is now considered an important ingredient for the evolution of galaxies with many models including this effect (e.g. Girichidis *et al.* 2018). Dwarf galaxies now significantly extend the studied parameter space as we show in Fig. 3. IC 10 fits approximately to the observed correlation of the advection speed with SFR and with rotation speed, but certainly not with SFR surface density, which deserves further investigation.

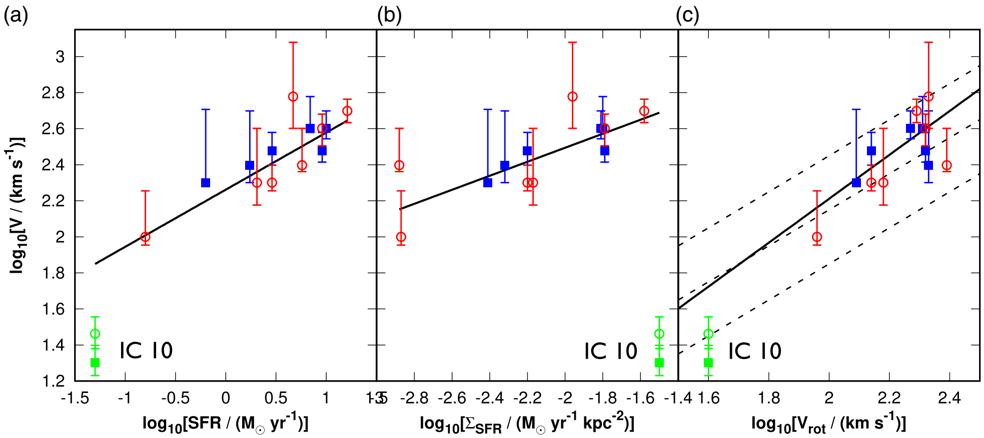

Figure 3. Advection speed in a sample of late-type and Magellanic-type galaxies from Heesen *et al.* (2018b) and IC 10 as function of SFR, SFR surface density ($\Sigma_{\rm SFR}$), and rotation speed ($V_{\rm rot}$). Solid lines represent best fits to the data except IC 10. In panel (c), we show also the escape velocity $V_{\rm esc} = \sqrt{2} \times V_{\rm rot}$, as well as $0.5 \times V_{\rm esc}$ and $2 \times V_{\rm esc}$ as dashed lines.

4. Conclusions

Cosmic rays play a key role in facilitating stellar feedback in galaxies. Their electron component can be observed as a proxy in the radio, where low-frequency observations are of particular interest since they are less affected by spectral ageing and contamination from thermal RC emission. Our work highlights the usefulness of RC observations, not only in measuring SFRs, a key galaxy evolution parameter, but also in detecting galactic winds – another important ingredient in galaxy evolution. We plan to make use of the ongoing LOFAR Two-metre Sky Survey (LoTSS; Shimwell *et al.* 2017) to expand our sample of galaxies to lower frequencies to test the wind models further, and to add more dwarf galaxies to determine whether IC 10 is a common or an exceptional case.

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