

The ISM of Dwarf Galaxies

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Abstract The state of the interstellar medium (ISM) of dwarf galaxies is reviewed, thereby emphasizing three different phases, namely the neutral, the hot and the nonthermal ISM. The distribution and structure of the more diffuse neutral ISM is discussed mainly on the basis of observations of the neutral hydrogen (HI), while that of the dense gas relies mostly on observations of the carbon monoxide (CO) line. Relations between the gas surface density and the star formation density are discussed, with ionized carbon (CII) identified as a powerful future tracer of the dense gas phase in star-forming galaxies. The hot X-ray-emitting gas is interpreted in terms of galactic winds driven by star formation and subsequent supernovae, making dwarf galaxies plausible candidates for the metal enrichment of the intra-cluster medium (ICM) in the early universe. The nonthermal phase of the ISM, comprising relativistic particles and magnetic fields is reviewed in the light of the possible role of dwarf galaxies in the magnetization of the ICM in the early universe, competing here with AGN. With *LOFAR*, a new low-frequency facility is becoming operational which will greatly aid to disclose the relativistic phase of the ISM also in dwarf galaxies.

1 Introduction

Being initially of interest for a “small family” only, dwarf galaxies have been very much in the focus of astrophysics over the past 20 years. The reason for this is twofold: first, they have constituted – and still do – the most numerous galaxy species in the early universe, according to a widely accepted structure formation scenario, in the framework of a Λ CDM cosmology. Second, owing to their shallow gravitational

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potentials, they are deemed the main “culprits for the pollution” of the intergalactic medium (IGM) with heavy elements.

Star-forming dwarf galaxies, generally referred to as dwarf irregular galaxies, are gas-rich almost by definition. Whereas the fraction of gas in large spirals amounts to about 10%, dwarf irregulars may have 50% or even more in some cases. These numbers have largely been inferred from HI observations, i.e. they refer to the content of diffuse, neutral atomic hydrogen. While it is clear that star formation works efficiently only in regions of dense molecular gas, this phase of the ISM has always been elusive. Yet, this cold and dense phase of molecular hydrogen (H_2) can almost solely be observed only indirectly, viz. via the second-most abundant molecule CO, owing to the lack of a dipole moment of the H_2 molecule. Tracing the molecular phase this way is, however, further impeded by the known low abundance of heavy elements in dwarf galaxies, implying both, a reduced dust formation (in turn necessary for H_2 formation) as well as a low CO abundance. The latter may be further reduced because of its lower self-shielding (as compared to H_2) against dissociating and ionizing radiation that can penetrate deep into the molecular clouds. It is thence not surprising that not a single CO detection has been reported for any dwarf galaxy with a metallicity below about $12 + \log[\text{O}/\text{H}] \approx 7.9$ [10, 49]. With a few exceptions and the caveat that tracing the molecular gas also depends on the local excitation conditions, essentially all of our knowledge about the gas phase in the low-metallicity ISM of dwarf galaxies results from observations of the HI line, and some inferences. The ionized hydrogen in HII regions tells us something about the ongoing star formation (as does the thermal free-free radiation also observed in the radio regime), while it is dynamically unimportant, such as (and even more so) the dust component.

The hot and nonthermal constituents of the ISM of dwarf galaxies are invariably connected with strong ongoing or recent star formation. It is the multitude of supernovae that heat the surrounding gas and produces relativistic particles, while at the same time driving dynamos and thus produce, maintain or amplify, the magnetic fields that we disclose via synchrotron radiation and Faraday rotation. While the hot phase has been studied observationally by using modern X-ray telescopes like *XMM-Newton* and *Chandra*, the relativistic plasma in dwarf irregulars has only been investigated in a few violently star-forming dwarfs. The problem here is that dwarf galaxies do not produce large amounts of relativistic particles in their quiescent phase, hence hardly emit synchrotron radiation during such epochs. The only means to trace such synchrotron-cooled particles is at the lowest frequencies using instruments such as *LOFAR*.

2 The Neutral ISM

2.1 The Neutral Atomic Hydrogen

The most recent and comprehensive studies of the neutral hydrogen of dwarf galaxies have been presented in the form of the Faint Irregular Galaxies GMRT Survey (FIGGS) [4, 5], and LITTLE THINGS [23] as part of THINGS, The HI

Nearby Galaxy Survey [54], which has been performed with the VLA in its B-, C-, and D-configuration. FIGGS contains 65 faint dwarf irregulars (dIrrs), measured with an angular resolution of $3''$ (but smoothed to $20''\dots 40''$ for the sake of better signal-to-noise ratios) and with an initial velocity resolution of 1.65 km s^{-1} . LITTLE THINGS provided maps with an angular resolution of $6''$, a velocity resolution of 5.2 km s^{-1} or better, and a typical $1\text{-}\sigma$ column density detection limit of $4\cdot 10^{19} \text{ cm}^{-2}$ at $30''$ angular resolution. It comprises 21 dIrrs and blue compact dwarf (BCD) galaxies, to which another 21 dwarfs were added from the archives.

Apart from such surveys, there are numerous case studies of the gaseous disks of dwarf galaxies in the literature. Some of these galaxies are particularly conspicuous because of their huge HI disks (compared to their stellar ones). Prominent examples are DDO 154 [13], and NGC 3741 [3, 21]. The latter, for instance, exhibits a warped HI disk with a size of some 42 optical scale lengths (Fig. 1). Obviously, there is a huge gas reservoir, perhaps orbiting in the gravitational potential of such a galaxy for a Hubble time, without having been used for star formation. Whether this is related to the Toomre criterion [51] needs to be investigated in each case. As far as the kinematics and mass distributions are concerned, such galaxies are extremely helpful in tracing the gravitational potentials out to very large distances. Yet, the derived rotation curves remain flat even in such galaxies (for a review on this topic, see [31]).

The typical velocity dispersion seen in dwarf galaxies is $\sigma_v \approx 6\dots 9 \text{ km s}^{-1}$. There is furthermore some evidence for two components [8, 56–58], namely a broad one with $\sigma_v \approx 9 \text{ km s}^{-1}$, which represents warm gas found throughout the entire HI

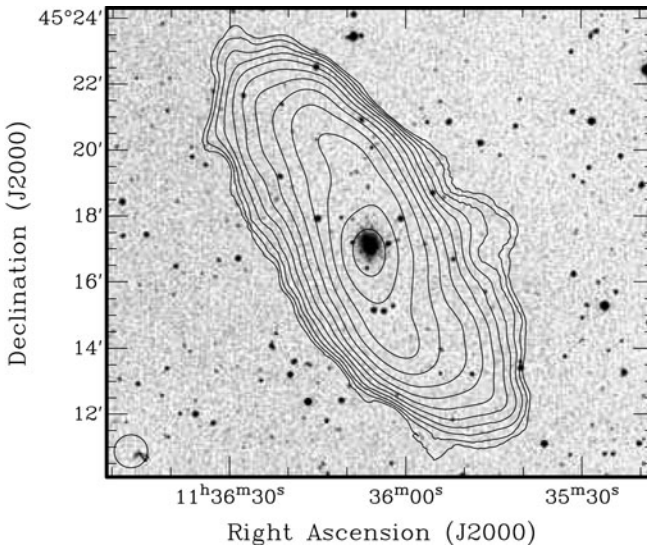


Fig. 1 HI column density map (contours) of NGC 3741, superimposed onto an optical image (from [21])

disk, and a narrow one with $\sigma_v \approx 4 \text{ km s}^{-1}$, representing cool and dense gas. There is no obvious spatial correlation between σ_v and the star formation rate per unit area.

The relation between star formation and gas distributions in dwarf galaxies has been discussed in quite some detail [7], based upon the THINGS project. They found that, while in spiral galaxies the star-formation efficiency (SFE) is a clear function of radius, dwarf galaxies exhibit SFEs similar to those found in the outer optical disks of spirals. In [7] this finding was attributed to similar physical conditions: low density and metallicity, and the prevalence of neutral atomic hydrogen. They furthermore argue that rotational shear, which is lacking in dwarf galaxies, cannot drive the SFE. A sharp saturation of the HI surface densities is established at $\Sigma_{HI} \approx 9 \text{ M}_\odot \text{ pc}^{-2}$ in both, spiral and dwarf galaxies. In the case of spirals, we observe gas in excess of this limit to be molecular.

The structure of the neutral atomic ISM in dwarf galaxies is mostly irregular, probably owing to their shallow gravitational potentials. They thus do not manage to build up any coherent structures, rendering the gaseous disks rather irregular and patchy. They are rather characterized by numerous “holes”. The properties of some 1,000 HI holes in 20 galaxies were analyzed [1], which have sizes from about 100 pc (the angular-resolution limit) to about 2 kpc, expansion velocities between 4 and 36 km s^{-1} , and estimated ages between 3 and 150 Myr. Holes are found out to the edges of the HI disks, and tend to be larger and rounder in dwarf galaxies, owing to the thicker disks and to the shallower gravitational potentials (see, e.g., [44]), as well as to the lower shear in these. While their origin in the inner star-forming disks is likely to be star formation, this is less clear in the outer gaseous disks, beyond R_{25} . Here, the underlying process could be shear and turbulence (see, e.g., [16]). In contrast, the holes cannot become so large in massive spirals, as they will be destroyed by the action of shear and density waves.

2.2 The Molecular Gas

Because of the lack of any dipole moment, the most abundant molecule of the ISM, H_2 , cannot be observed in emission, at least not under physical conditions that would be representative for the general ISM. One therefore has to resort to indirect methods, foremost by observing the CO molecule, which is the second-most abundant. To this end, a well established relation between the measured CO brightness and the inferred H_2 column density is being used, even out to cosmological distances.

In dwarf galaxies, however, even this method is rarely applicable because these are generally faint emitters in the CO line. The reason is manifold: their lower abundance of heavy elements results in a lower CO abundance and, at the same time, in a lower formation of dust. The lower dust abundance in turn leads to a reduced shielding of the CO against dissociation by UV radiation. As a result, H_2 may be concealed over large parts of dwarf galaxies, with CO emission only present in those regions that have the physical conditions for CO to survive and

to be excited. An impressive example for this is the LMC, in which CO emission has been found in few localized regions (see, e.g., [20]), while there is HI and star formation over much of the disk. In fact, emission in the [CII] line (ionized carbon) is seen in essentially all star-forming regions of the LMC [38]. The most complete census of molecular gas in the LMC via the CO line is currently underway. In a project called “The Magellanic Mopra Assessment” (MAGMA [55]) the ATNF 22-m Mopra telescope is used to survey all CO-emitting regions in both, the Large and the Small Magellanic Cloud, thereby providing the highest spatial resolution of such a survey outside the Milky Way.

A CO survey of 121 northern dwarf galaxies has been published [33], of which they detected 28, and 12 marginally. They found a strong correlation of the CO luminosity with that in the K-band and in the FIR, and a weaker one with the 1.4-GHz and B-band luminosity. Their inference from this is that deeper gravitational wells of the stellar disks lead to a higher gas pressure, hence to a higher gas density. The increased gas density then results in an enhanced more H₂ formation [22].

No substantial changes of the conversion ratio $X_{CO} = N_{H_2}/I_{CO}$ are seen for metallicities in the range $0.25 Z_{\odot} < Z < Z_{\odot}$. The conjecture is that in order to detect the molecular gas in such galaxies one needs another tracer. This could be cold HI, cold dust (a very indirect method), or the [CII]-line at 158 μm .

The best conditions to (indirectly) find H₂ appear to prevail in strongly star-forming dwarf galaxies, such as NGC 1569 [39] and NGC 4449 [9]. NGC 1569 is a prototypical starburst dwarf galaxy exhibiting all of the corresponding features. Essentially its whole body is emitting intense radio (synchrotron and free-free) and H α radiation. It possesses an extended X-ray halo (e.g. [15]). The outflow velocities in NGC 1569 were found to exceed the escape speed [35, 36], and the temperature of its hot gas to exceed the virial temperature [15]. As far as the molecular gas is concerned, Fig. 2 illustrates the situation in NGC 1569 pretty well: there appears to be copious molecular gas filling the central star-bursting volume of the galaxy, however, with a pronounced central “hole”, coincident with the two prominent super-star clusters driving the starburst. This region, which also marks the foot point of the outflow, is embraced by what might be considered to be “molecular walls”.

Another star-forming dwarf galaxy, NGC 4214 exhibits three CO-emitting regions with distinct properties [53]: one in which no signs of current star formation are evident, one with star formation that has commenced recently, and one with evolved star formation, in which the CO intensity is clearly seen to be reduced within the brightest HII regions.

Molecular gas in BCDs is also difficult to trace, owing to their intense UV radiation field. CO(1 $\rightarrow$ 0) and CO(2 $\rightarrow$ 1) emission was searched for in a sample of eight HI-rich BCDs [2], with only two of them detected. They found that the conversion ratio X_{CO} is similar to that of the Milky Way. A thorough CO(1 $\rightarrow$ 0) and CO(2 $\rightarrow$ 1) study of Haro 2 [19] revealed the kinematic axis of the molecular gas seen in the center to be almost perpendicular to that of the outer HI (see Fig. 3), which is indicative of gas accretion or a merger. This was later on confirmed [11] and is similar to what has been inferred for He 2-10 [52].

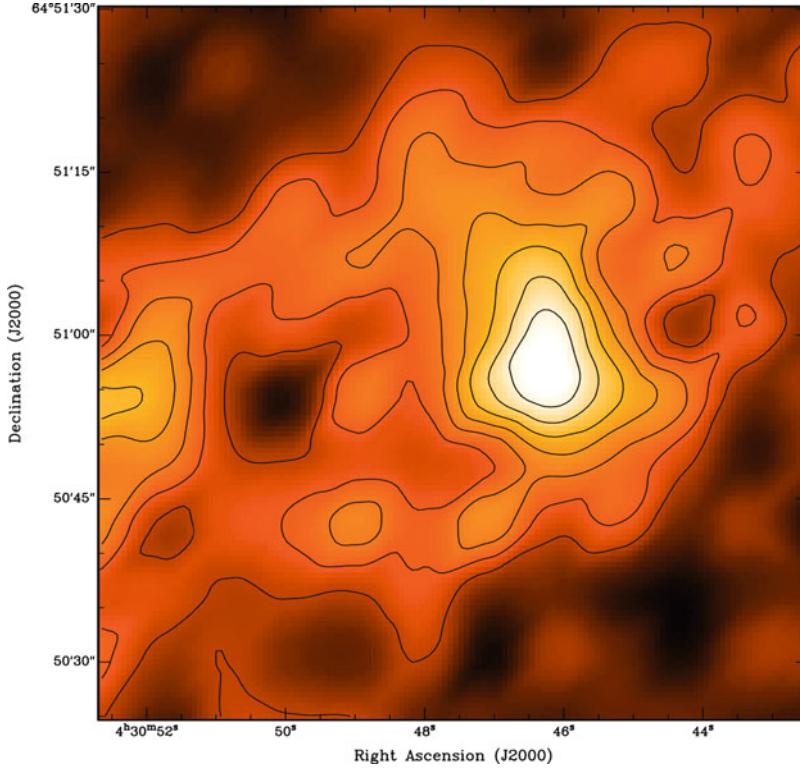


Fig. 2 CO(2→1) map of NGC 1569 [39]

3 The Hot ISM

Starburst dwarf galaxies have a particularly strong feedback on the ISM by massive stars, i.e. stars more massive than $\sim 8 M_{\odot}$. Much of the energy from their stellar winds and supernovae is thermalised, thereby producing X-ray-emitting hot gas, with temperatures of several 10^6 K. This gas expands into the surroundings of the galaxies, forming so-called coronal gas (e.g. [47]). In extreme cases, this may go along with a galactic wind in which dwarf galaxies may lose (part of) their metal-enriched gas to the IGM (e.g. [34, 45]). Consequently, dwarf galaxies have been in the focus of investigations of this hot gas in galaxies, with well-known starburst dwarfs used as targets. A lot of progress was made with the availability of the *Chandra* X-ray observatory with its unprecedented angular resolution (e.g. NGC 1569: [37]; NGC 4449: [48]; I Zw 18: [50]).

In an effort to study the properties of the hot coronal gas in a sample of dwarf galaxies, all of which had previously been observed with *Chandra*, the *Chandra* X-ray data of the eight dwarfs (I Zw 18, VII Zw 403, NGC 1569, NGC 3077,

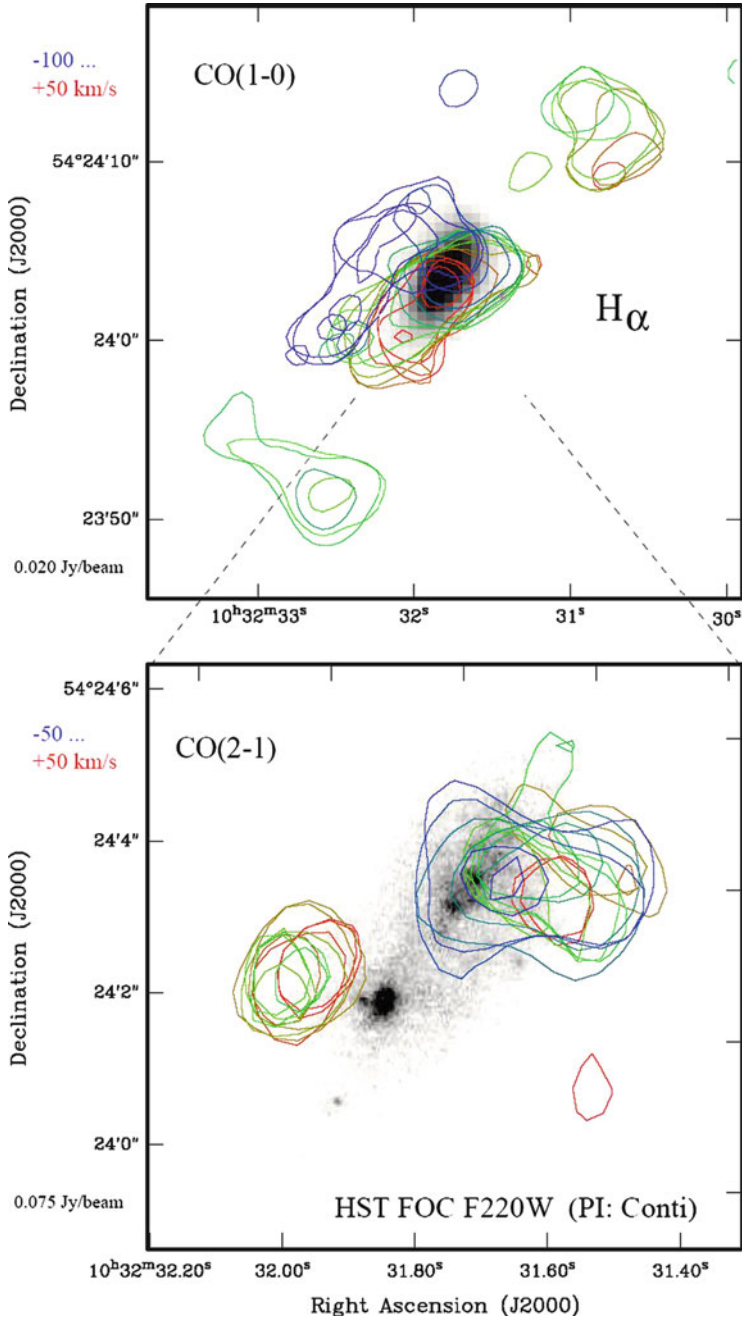


Fig. 3 Maps of the CO(1 $\rightarrow$ 0) and CO(2 $\rightarrow$ 1) emission of Haro 2 (from [19]). The “renzogram” contours indicate different radial velocities, increasing from red (receding) to blue (approaching)

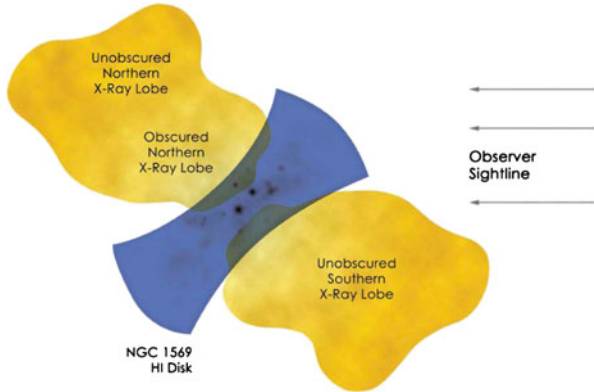


Fig. 4 X-ray shadow and orientation of NGC 1569 (from [37])

NGC 4214, NGC 4449, NGC 5253, He 2-10) were reduced in a uniform way [41,42]. In this analysis, all but two of these were found to possess extended, diffuse X-ray emission, with extents of $1 \dots 10$ kpc, temperatures of $(2 \dots 3) \cdot 10^6$ K, and metallicities similar to those of HII regions (for previous investigations of the X-ray emission from these galaxies see the references in [41]).

Again, the investigation of the prototypical starburst dwarf NGC 1569 is of crucial importance. Its starburst ceased about $5 \cdot 10^6$ yr ago, as inferred from the break in its synchrotron spectrum [24]. Its two super-star clusters mentioned above have produced the central 190-pc hole visible in both, the HI [25] and the CO [39], thereby producing a wind of hot gas (e.g. [36]). A long-standing problem used to be its apparent isolated location at a distance of 2.2 ± 0.6 Mpc. A new distance determination via the tip of the red-giant branch now yields 3.36 ± 0.20 Mpc, thus placing it in the IC 342 group. The starburst could thence be a tidally induced one. Furthermore, NGC 1569 is a nice example to utilize X-ray absorption for an assessment of the orientation of a galaxy in space. While its disturbed kinematics as deduced from HI observations is too disturbed to allow any determination of its inclination angle (e.g. [40]), its X-ray shadow clearly reveals its true orientation [37]. Its northern X-ray halo is strongly dimmed by X-ray absorption, due to the gaseous disk, while its southern coronal gas is seen largely unaffected by this process (Fig. 4).

4 The Nonthermal ISM

Dwarf galaxies also emit radio (synchrotron and free-free) emission during their star-formation periods, and for some time thereafter. Measurements of the radio continuum radiation of dwarf galaxies over a large frequency range have shown that ongoing star formation in them is accompanied by enhanced radio continuum

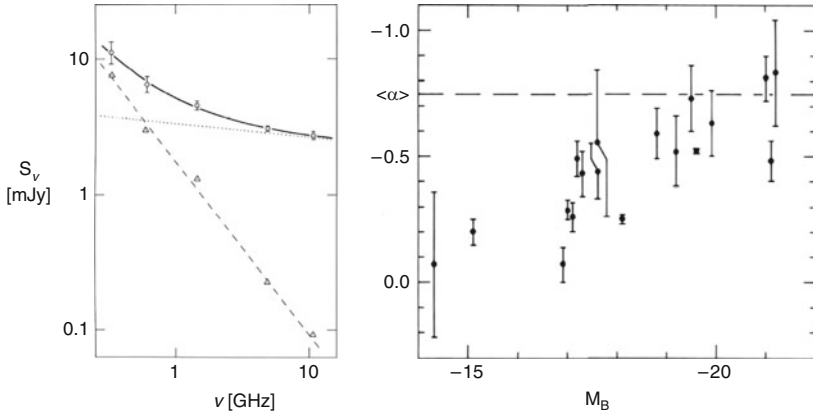


Fig. 5 *Left*: radio continuum spectrum of the BCD II Zw 70, with the thermal (free–free, *dotted line*), nonthermal components (synchrotron, *dashed line*) and their sum indicated (from Skillman and Klein [46]). *Right*: spectral indices of the integrated radio emission of a sample of low-mass galaxies, mostly BCD (from [28])

emission [27]. Owing to their shallow gravitational potentials, the containment of relativistic cosmic-ray particles in such galaxies is, however, low, as inferred from studies of their synchrotron spectra [28] and their magnetic-field structure [26]. Figure 5 demonstrates this: in contrast to massive spiral galaxies, whose radio continuum is dominated by synchrotron radiation at cm wavelengths [18], there is a lack of it for dwarf galaxies.

This lack is more pronounced at lower masses of dwarf galaxies. The escaping relativistic particles form synchrotron halos around dwarf galaxies (NGC 4449: [30], NGC 1569: [26]) and lose their energy on a time scale of $\sim 10^8$ year via synchrotron and Inverse-Compton radiation. They are thus quickly rendered invisible at cm wavelengths, while their synchrotron emission will still be detectable at metre waves where their lifetime is 5 to 10 times longer. Dwarf galaxies with low current star formation rates are very radio-dim (e.g. [29]).

The structure of magnetic fields in dwarf galaxies has been explored for only the brightest, hence most vigorously star-forming, ones. These are the usual templates NGC 1569 ([26], see Fig. 6) and NGC 4449 [14], and the low-mass starburst galaxy M 82 [43]. They all have projected radial magnetic fields in common, in contrast to massive spirals, in which the magnetic fields follow the spiral arms. The strengths of the magnetic fields in such star-bursting dwarf galaxies can be as high as several tens of μG , while they are of order a few μG in quiescent dwarf galaxies.

The following two properties render dwarf galaxies potentially very efficient in injecting the relativistic plasma into the intra-group or cluster environment: first, they exist in large numbers (in particular in the early universe), and second, they possess low escape velocities, making it easier to expel their interstellar gas, as compared to massive spiral galaxies. As mentioned above, such galactic winds are in fact seen in some prototypical low-mass galaxies in the local universe.

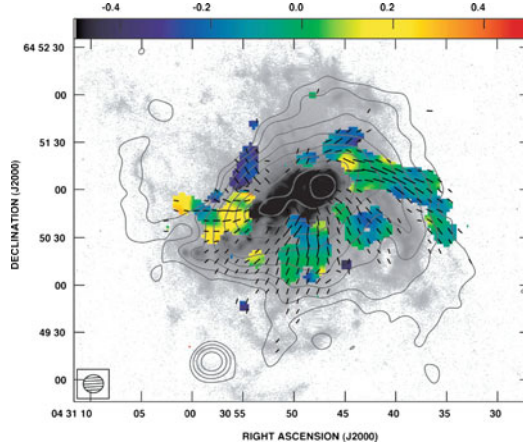


Fig. 6 Structure of the magnetic field in NGC 1569 (“vectors”), superimposed onto an $H\alpha$ image. The contours delineate the $\lambda 3$ -cm emission, while the colour scale represents the rotation measure in units of 10^3 rad m^{-2} (from [26])

Dwarf galaxies may thus have been an efficient species to magnetize the IGM, in competition with AGN. The presence of large pools of (formerly) relativistic particles and magnetic fields is inferred from a number of observational evidences, such as Faraday rotation in galaxy clusters, synchrotron radio halos and peripheral sources, so-called “relics”, in merging or dynamically unrelaxed clusters of galaxies. Such injection models have meanwhile been presented by a number of authors [6, 17, 32].

5 The Potential of Low-Frequency Radio Astronomy

We are facing an exciting period, with new astronomical instrumentation being developed. One of these is *LOFAR* (Fig. 7), which starts to explore the somewhat neglected low-frequency regime of radio astronomy. Covering the frequency range of $30 \dots 80 \text{ MHz}$ and $120 \dots 240 \text{ MHz}$, *LOFAR* will easily detect low-frequency halos of dwarf galaxies out to large distances (100 Mpc, Coma Cluster). Low-frequency radio emission “memorises” starburst activity up to about 1 Gyr after its termination, a time scale much longer than that of any other tracer of star formation in galaxies ($H\alpha$ and FIR luminosity, or broad-band optical/UV/IR colours). This emission therefore also provides a powerful diagnostic tool to search for post-starburst galaxies and to explore their recent-to-past star-formation rate and magnetic field evolution.

The *LOFAR* survey, which will cover about half the sky and will be conducted in the near future, will provide a $5\text{-}\sigma$ flux limit of 0.1 mJy/b.a. at 120 MHz in 1 hour (with a synthesized beam of $1''.3$, for long baselines). Using the synchrotron halo



Fig. 7 *LOFAR* station deployed by the MPIfR Bonn at the site of the Effelsberg 100-m telescope

of NGC 4449 as a template, we can estimate the expected brightness of such halos at *LOFAR* frequencies which, for instance, is about 0.4 mJy/b.a. at 120 MHz. Its detection should hence be readily feasible. Assuming a 60 kpc diameter (that one can estimate from the diffusion properties of the relativistic particles) as estimated above and placing it at $D \approx 100$ Mpc it would be seen with a $\sim 2'$ angular extent. In a cluster or group environment, such halos are likely to trail behind the galaxy as it moves in the cluster potential with speeds much larger than the diffusion speed of the relativistic particles.

In this context, *LOFAR* may also add important new information to address the long-standing question pertaining to possible evolutionary links between the two main classes of late-type dwarf galaxies, dwarf irregulars (dIs) and BCDs. BCDs in a post-starburst phase will be easily identifiable by their weak radio emission at cm wavelengths in conjunction with their bright radio halos at meter wavelengths. By contrast, the synchrotron radiation of non-starbursting late-type dwarf galaxies will be undetectable at cm wavelengths, while their low-frequency radio continuum emission should still exhibit the synchrotron halos created during past activity phases. Hence, if the standard evolutionary scenario, i.e. from BCDs to dIs, is correct, then *LOFAR* will discover a large population of quiescent dIs with low-frequency radio halos.

Before *LOFAR* is becoming fully operational, we are utilizing the *WSRT* at 350 MHz such as to provide a good frequency coverage in the low-frequency domain. This is not only important to scrutinize the synchrotron spectra, but is indispensable to perform Faraday rotation measure synthesis [12].

6 Concluding Remarks

From the above it is clear that dwarf galaxies will remain in the focus of astrophysics for various reasons. Lacking large-scale spiral density waves and rotational shear, they serve as astrophysical laboratories that allow us to study star formation and galaxy evolution in the absence of mechanisms that continuously stir up the gas in their disks. Their winds appear to keep the abundances of heavy elements at

low levels, thus providing conditions in which we can study this evolution in low-metallicity environments. Their gaseous disks extend significantly beyond the stellar ones and are thick compared to those of normal spiral galaxies, which allows us to study their kinematics out to large relative galacto-centric distances, and at the same time far into their halos. Their shallow gravitational potentials are not only responsible for the production of galactic winds, but may also make them “culprits” for the magnetization of the IGM in the early universe, in competition with AGN.

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