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A fresh view of magnetic fields and cosmic ray electrons in halos of spiral galaxies

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Abstract. Recent numerical models of the multiphase ISM underline the importance of cosmic rays and magnetic fields for the physics of the ISM in disc galaxies. Observations of properties of the ISM in galactic halos constrain models of the expected exchange of matter between the star-forming disc and the environment (circumgalactic medium, CGM). We present new observational evidence from radio-continuum polarization studies of edge-on galaxies on magnetic field strength and structure as well as cosmic ray electron transport in galactic halos. The findings are discussed in the context of the disk-halo interaction of the interstellar medium. In addition, it is also briefly demonstrated how recent LOFAR observations of edge-on galaxies further constrain the extent of magnetic fields in galactic halos.

Keywords. galaxies: magnetic fields, galaxies: spiral, galaxies: halos, radio continuum: galaxies

1. Introduction

In the context of galaxy formation scenarios various feedback mechanisms (e.g., Silk 2013) have been discussed to explain the observed dependence of the global and long-term star formation efficiency in dark halos of different mass expressed as the ratio of stellar mass to the mass of the dark matter halo (e.g., Behroozi *et al.* 2013; Moster *et al.* 2013). For disc galaxies many different processes related to star formation are proposed: besides supernova explosions, stellar winds, and radiation pressure a number of recent papers discuss the possible importance of magnetic fields and cosmic ray pressure as an additional factor for the global dynamics of the interstellar medium (ISM) as well as for the launching of galactic winds (e.g., Girichidis *et al.* 2016; Pakmor *et al.* 2016). In the following we discuss the possible evidence for such cosmic ray driven galactic winds as observed by cosmic ray electrons (CREs) propagating in the magnetic fields in galactic halos. Recent progress in instrumentation such as the introduction of broad-band multi-channel receivers at all large radio facilities allow for a fresh look at this long standing problem. Progress has also been made with regard to the wavelength coverage: with LOFAR (van Haarlem *et al.* 2013) it is now possible to observe the emission from CREs at lower energies which are less affected by energy losses. They represent an old population that has traveled furthest from the site of origin in the star forming regions of the mid-plane.

2. Transport models for cosmic ray electrons

The polarized and frequency dependent radio-synchrotron radiation of CREs allows us to constrain the magnetic field strength and structure in galaxies. The frequency dependence of the synchrotron intensity also contains information on the transport processes for the CREs (e.g., Beck 2015). However, the observed emission has to be corrected for the frequency dependent contribution of the thermal radio-continuum which is also strongly correlated with star-formation. Here considerable progress has been made due to the availability of infrared data from satellite observations such as *Spitzer* and *WISE*. The dust emission in the ISM is a very good proxy for the star formation rate and can thus be used to correct for the thermal emission (e.g., Vargas *et al.* 2018). The clean synchrotron emission at various frequencies can then be used to study the emission by CREs with regard to magnetic field strengths and cosmic ray propagation processes such as diffusion or advection.

In a case study of the southern edge-on galaxies NGC 7090 and NGC 7462 based on Australia Telescope Compact Array (ATCA) data, Heesen *et al.* (2016) demonstrated that advective and diffusive transport of cosmic ray electrons into the halo can be distinguished by fitting a 1-D cosmic ray transport model to the intensity and spectral profiles perpendicular to the galaxy disc. Based on the analysis of archival data from the Very Large Array (VLA) and the Westerbork Synthesis Radio Telescope (WSRT), Heesen *et al.* (2018) discuss results of a larger sample (Fig. 1) with the conclusion that the radio halos of most galaxies studied so far are best described by advective transport models. For these galaxies the bulk velocity of the cosmic ray electrons correlates with the escape velocity of the galaxies as expected for galactic winds.

3. The CHANG-ES survey: first results

This analysis method is now to be applied to observations from the Karl G. Jansky Very Large Array (VLA) in the context of the "Continuum HAlos in Nearby Galaxies – an Evla Survey" (CHANG-ES) project. The CHANG-ES sample consists of 35 edge-on spiral galaxies in the local universe selected by angular size and total flux. The targets were observed in the B-, C- and D-array-configurations in C- and L-band (Irwin *et al.* 2012). First results for the complete sample have been presented by Wiegert *et al.* (2015) in combination with a first data release of the D-array data products. The study provides an image of an averaged radio-continuum halo or thick disk for the sample. The conclusion that the average edge-on galaxy exhibits an extended radio-continuum halo is different from the finding by Singal *et al.* (2015) claiming that edge-on galaxies do not possess radio-continuum thick disks or halos that would make the emission look similar to that observed in the Milky Way. Further analyses study general properties of the CHANG-ES sample such as typical scale heights of the radio-continuum disks (Krause *et al.* 2018) as presented in another contribution to this meeting (Krause 2018). The case study of NGC 4666 based on CHANG-ES data with an indication of a possible reversal of the magnetic field direction in the plane of the disk is also presented elsewhere in these proceedings by Stein *et al.* (2018). A more detailed description of the CHANG-ES project and of its first results is presented by Stil *et al.* (2018) at this conference.

4. Magnetic fields in galactic halos

Radio-continuum halos of star-forming disc galaxies frequently exhibit a large scale X-shaped magnetic field as, e.g., described for the prototypical case of NGC 5775 in Tüllmann *et al.* (2000). The extent of the synchrotron emission itself is proof for the presence of a magnetic field reaching far into the halo. Since the low energy cosmic rays are expected to be transported furthest, studies of the corresponding low frequency

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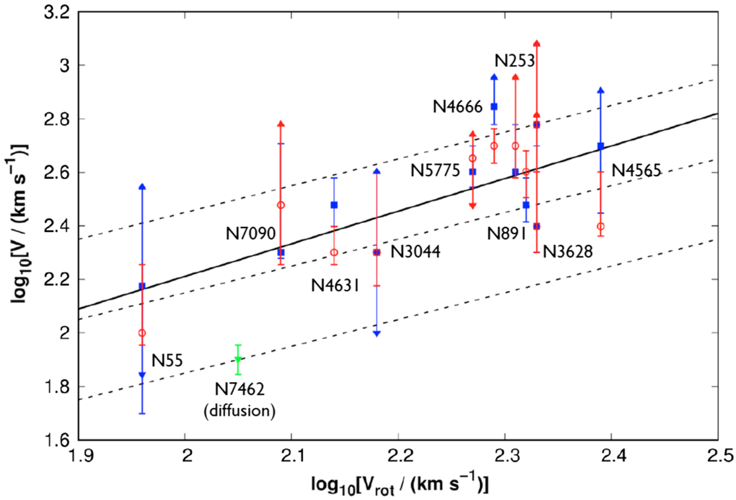

Figure 1. The correlation of the advection speed of cosmic ray electrons with the maximum rotation speed, i.e. total mass, of a sample of galaxies studied by Heesen *et al.* (2018). Most galaxies in this sample are best described by advective models for the cosmic ray electron propagation.

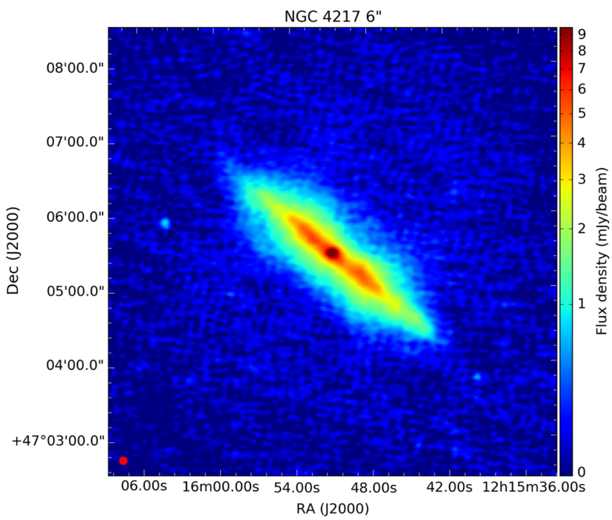

Figure 2. The edge-on galaxy NGC 4217 with a dumbbell-shaped radio-continuum halo is observed by LOFAR at 145 MHz as part of the Data Release 1 of the LoTSS survey (Shimwell *et al.* 2017; Shimwell 2018). The reprocessing by A. Miskolczi resulted in the reproduced map with a noise level of $\sim 70\mu$Jy/beam at 6 arcsec resolution.

emission allow us to probe the magnetic field far into the halo. LOFAR now provides observations with unprecedented sensitivity and resolution at such low frequencies as, e.g., demonstrated by the study of NGC 891 (Mulcahy *et al.* 2018). The LOFAR LoTSS survey (Shimwell *et al.* 2017) will provide a very good base for in depth studies of many more edge-on galaxies. To demonstrate this potential, Fig. 2 shows a map of NGC 4217 observed as part of the LoTSS Data Release 1 (Shimwell 2018). The dumbbell-shape radio halo (or thick disk) results from the combined effect of a radial decline of the magnetic field strength and the energy losses of the CREs transported into the halo (see Heesen *et al.* 2009a,b for a more detailed discussion).

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