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A TWOFOLD APPROACH TO MAGNETIC FIELDS IN NEARBY GALAXIES

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Abstract

Magnetic fields are a fundamental component of galaxy evolution: they regulate star formation, shape interstellar turbulence, and channel feedback through galactic outflows; yet their amplification mechanisms and coupling to the multiphase interstellar medium (ISM) remain poorly constrained. This doctoral thesis investigates magnetic fields in nearby galaxies through two complementary but independent approaches: parsec-scale polarimetric observations that resolve magnetic geometry and depolarization in a nuclear starburst, and cosmological magnetohydrodynamical (MHD) simulations that quantify how magnetic energy scales with star formation and ISM conditions.

We review large and small-scale dynamo theory, energy-equipartition arguments, and the main observational tracers (synchrotron and dust polarimetry, Faraday rotation, Zeeman splitting), establishing the physical and methodological context for the analyses that follow.

We present full-Stokes ALMA polarimetry of the nuclear starburst in NGC 253 at Band 4 (≈ 145 GHz; ≈ 25 pc resolution) and Band 7 (≈ 345 GHz; ≈ 5 pc resolution). Both bands reveal a consistent plane-of-sky magnetic geometry aligned with the base of the biconical outflow. The polarization fraction anti-correlates with column density and with polarization-angle dispersion, indicating depolarization dominated by field tangling on ~ 25 pc scales, with additional effects emerging at ~ 5 pc. Minima near super star clusters point to feedback-driven magnetic complexity.

Using 19 zoom-in galaxies from the AZAHAR suite, we quantify magnetic, turbulent, thermal, and cosmic-ray energies and their links to star formation. The simulations yield near-universal scalings $B \propto \text{SFR}^{0.2-0.3}$ and $B \propto \Sigma_{\text{SFR}}^{1/3}$, consistent with supernova-driven, turbulence-regulated amplification. Neutral gas is typically turbulence-dominated, with magnetic and cosmic-ray energies approaching equipartition in vigorously star-forming systems. These trends match observed slopes and normalizations across spirals, dwarfs, and starbursts.

These theoretical, observational, and numerical results converge toward a coherent picture in which magnetic fields act as active agents that both trace and regulate star formation and feedback across multiple scales and environments.

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Introduction

Magnetic fields in galaxies matter

Magnetic fields thread every component of the interstellar medium (ISM) and play a crucial yet often underestimated role in shaping the life cycle of galaxies. They guide the flow of charged particles, regulate the collapse of molecular clouds, and influence the rate and efficiency of star formation. Through their pressure and tension forces, they help support gas against gravity, channel feedback-driven winds, and control how matter and energy are exchanged between the disk and halo. Although magnetic energy is typically subdominant on galactic scales, within the dense, turbulent ISM it can approach equipartition with thermal and kinetic energies, making it dynamically significant.

Observationally, the past decade has brought remarkable progress in tracing magnetic fields across different phases of the ISM. Radio synchrotron and Faraday-rotation measurements reveal large-scale ordered fields in nearby spiral galaxies, typically $\sim 5 \mu\text{G}$ in strength, coexisting with stronger total fields of order $\sim 10 - 20 \mu\text{G}$ when including turbulent components (Beck et al., 2019; Shukurov & Subramanian, 2021). Edge-on systems frequently exhibit striking X-shaped halo geometries, where magnetic lines extend several kiloparsecs from the galactic plane (Heesen et al., 2009; Beck et al., 2019; Krause et al., 2020). In starburst nuclei, polarisation observations indicate field strengths reaching hundreds of microgauss, with magnetic energy densities comparable to turbulent and cosmic-ray pressures; such strong fields can collimate and regulate galactic outflows (Heesen et al., 2011; Lopez-Rodriguez et al., 2021; Lopez-Rodriguez, 2023).

Despite these advances, many key questions remain unanswered. How are magnetic fields structured and amplified within the dense, star-forming centres of galaxies? What is their true role in driving or constraining starburst activity? And to what extent do they couple to the surrounding multiphase gas on parsec to kiloparsec scales?

Thesis approach

Understanding the structure and role of magnetic fields in galaxies requires both high-resolution observations and physically grounded theoretical models. This thesis addresses this challenge by using high-resolution polarisation observations and synthetic diagnostics derived from state-of-the-art magnetohydrodynamical (MHD) simulations.

These are the two main approaches that we will follow:

- **Observational analysis of the prototypical starburst galaxy NGC 253.**

We analyse full-polarisation ALMA observations in Bands 4 ($\nu \simeq 145$ GHz, resolution $\sim 1.5'' \times 1.3'' \approx 25$ pc) and 7 ($\nu \simeq 343.5$ GHz, resolution $\sim 0.32'' \times 0.28'' \approx 5$ pc). These datasets represent one of the highest-resolution, full-polarisation views of a nearby galaxy achieved to date. From them, we produce parsec-scale polarimetry maps, derive the plane-of-sky magnetic-field orientation with pixel-level uncertainty estimates, and analyse both native and matched-resolution datasets. We further perform spectral energy distribution (SED) fitting to disentangle the dust, synchrotron, and free-free emission components, linking the inferred magnetic field morphology to the nuclear outflow and to the spatial distribution of super star clusters (SSCs).

- **Theoretical characterisation through cosmological zoom-in simulations.**

We use a suite of high-resolution MHD simulations to generate line-of-sight integrated, observation-like maps for a representative sample of 19 spiral galaxies. For each system, we identify the inner star-forming disk and measure key physical quantities, including the median magnetic-field strength, and the thermal, turbulent, magnetic, and cosmic-ray specific energies, as well as the star-formation rate (SFR), its surface density (Σ_{SFR}), and specific SFR (sSFR). These diagnostics are compared with observational samples of nearby galaxies, including both normal spirals and starburst systems similar to NGC 253, establishing a consistent and physically motivated framework that links simulated and observed magnetic-field scaling relations across diverse galactic environments.

Through these two approaches, this thesis aims to address a series of key research questions designed to improve our understanding of the magnetic field.

Research questions (RQs).

1. **RQ1:** How is the morphology of galactic magnetic fields shaped by the interplay between star formation, gas dynamics, and feedback in dense nuclear environments?

2. **RQ2:** Which processes (e.g. dust-grain alignment efficiency, turbulence, shear, outflow advection) regulate the observed polarisation properties, and what do they reveal about the efficiency of grains alignment in dense environments?
3. **RQ3:** To what extent do dust and synchrotron polarimetry trace the same underlying magnetic-field geometry across frequencies and environments?
4. **RQ4:** How do magnetic fields correlate with gas density, turbulence, and star-formation tracers in galaxies?
5. **RQ5:** Under what conditions do magnetic fields become dynamically important within galaxies? How do they compare to turbulent, thermal and cosmic rays energies?
6. **RQ6:** How do magnetic–star-formation scaling relations vary between the cold and warm neutral media?

Thesis structure

Given the twofold approach employed in this work, the thesis is organised into two main parts, each addressing complementary aspects of galactic magnetism. The first part focuses on the *observational characterisation* of magnetic fields in the nearby starburst galaxy NGC 253, while the second part develops a *theoretical framework* based on simulations to interpret and generalise the observed trends.

Chapter 1 establishes the theoretical foundations of galactic magnetism, outlining the physical principles of large- and small-scale dynamo theory, the observed correlations between magnetic fields and star formation, and the role of magnetic, turbulent, and cosmic-ray energy equipartition in the interstellar medium.

Observational Framework

Chapter 2 reviews the main observational tracers of magnetic fields and their use in the study of galactic magnetism. A short summary of ALMA instrumentation and polarimetric calibration procedures is also included. Chapter 3 presents the analysis of full-Stokes ALMA observations of NGC 253, deriving parsec-scale maps of polarised emission, magnetic-field orientation, and depolarisation diagnostics, and linking them to the galaxy’s star-formation activity and multiphase outflow.

MHD Simulations and Synthetic Diagnostics

Chapter 4 introduces the MHD framework underlying galaxy-formation simulations,

detailing the governing equations, numerical methods, and the implementation of the cosmological MHD model used in this work. Chapter 5 explores the scaling between magnetic fields and star formation for a sample of simulated galaxies, quantifying the energy budgets across ISM phases and comparing the synthetic results with observations.

The final Chapter 6 synthesises the observational and numerical results, emphasising the physical connection between magnetic-field amplification, star formation, and outflow dynamics, and introduces forthcoming ALMA–VLA joint polarimetric observations that will extend this work, together with future developments in MHD simulations.

List of Acronyms and Abbreviations

- ALMA** – Atacama Large Millimeter/submillimeter Array.
AME – Anomalous Microwave Emission.
CDM – Cold Dark Matter.
CGM – Circumgalactic Medium.
CHANG-ES – Continuum Halos in Nearby Galaxies – an EVLA Survey.
CNM – Cold Neutral Medium.
DCF – Davis–Chandrasekhar–Fermi Method.
FIR – Far-Infrared.
FUV – Far-Ultraviolet.
FWHM – Full Width at Half Maximum.
HAWC+ – High-resolution Airborne Wideband Camera Plus.
HIM – Hot Ionized Medium.
HI – Neutral Atomic Hydrogen.
HII – Ionized Hydrogen.
HST – Hubble Space Telescope.
ICM – Intracluster Medium.
IGM – Intergalactic Medium.
ISM – Interstellar Medium.
LOS – Line of Sight.
LSD – Large-Scale Dynamo.
MDE – Magnetic Dipole Emission.
MHD – Magnetohydrodynamics.
MRS – Maximum Recoverable Scale.
MW – Milky Way.
PAH – Polycyclic Aromatic Hydrocarbon.

PF – Polarisation Fraction.
PI – Polarised Intensity.
POS – Plane of Sky.
RAT – Radiative Alignment Torque.
RM – Rotation Measure.
RMS – Root Mean Square.
SALSA – Survey of extragalactic magnetic fields with SOFIA.
SED – Spectral Energy Distribution.
SFH – Star Formation History.
SFR – Star Formation Rate.
SN – Supernova.
SOFIA – Stratospheric Observatory for Infrared Astronomy.
SSD – Small-Scale Dynamo.
TDM – Time Division Mode.
VLA – Very Large Array.
WIM – Warm Ionized Medium.
WNM – Warm Neutral Medium.

1

Physics and origin of magnetic fields

A solid understanding of the physical processes that govern the origin, amplification, and observable signatures of galactic magnetic fields is essential to place both observations and simulations in context. In this chapter we outline the theoretical framework that connects seed-field generation, dynamo amplification, and the energy balance of the interstellar medium. Section 1.1 summarises the observational evidence for long-lived, coherent galactic magnetic fields and motivates the need for in-situ amplification to overcome turbulent diffusion. Section 1.2 develops the large-scale (mean-field) dynamo, highlighting the roles of differential rotation and helical turbulence, growth and saturation timescales, and expected observables. Section 1.3 turns to the small-scale (fluctuation) dynamo, describing rapid kinematic growth, nonlinear saturation, and the characteristic tangled, intermittent field it produces. Section 1.4 presents scaling relations that link magnetic fields to star-formation activity via turbulence driving, providing a bridge between theory and the empirical radio/FIR trends. Section 1.5 places magnetic energy within the broader interstellar medium energy budget (thermal, turbulent, and cosmic rays), introducing diagnostic ratios that will be used throughout this thesis. Finally, Section 1.6 discusses magnetised galactic outflows, their role in transporting flux to the halo and in regulating dynamo saturation, and their observational signatures in nearby starbursts.

1.1 Introduction

The presence of large-scale magnetic fields in galaxies is firmly established through multiple observational tracers, most prominently synchrotron emission, Faraday rotation, and polarised dust emission (discussed in detail in Chapter 2). These reveal coherent magnetic structures that extend over kiloparsec scales and persist across cosmic times ([Beck, 2015](#)). From a theoretical perspective, however, such ordered fields should not survive indefinitely: turbulent motions in the interstellar medium (ISM) contribute to the dissipation of magnetic fields through turbulent diffusion. Random eddies continuously mix magnetic flux, redistributing field lines and erasing coherence on scales larger than

the turbulent driving scale. The relevant timescale is the turbulent diffusion time,

$$t_{\text{diff}} \sim \frac{h^2}{\eta_t} \quad \text{with} \quad \eta_t \simeq \frac{1}{3} v_{\text{turb}} \ell_{\text{turb}}, \quad (1.1)$$

where h is the vertical scale height of the gaseous disk, v_{turb} the turbulent velocity, and ℓ_{turb} the turbulence correlation length. For typical disk parameters ($h \sim 0.5\text{--}1$ kpc, $v_{\text{turb}} \sim 10 \text{ km s}^{-1}$, $\ell_{\text{turb}} \sim 50\text{--}100$ pc), this yields $t_{\text{diff}} \sim 0.1\text{--}1.0$ Gyr [Elmegreen & Scalo \(2004\)](#); [Brandenburg & Subramanian \(2005\)](#); [Tamburro et al. \(2009\)](#); [Beck \(2015\)](#). This is about an order of magnitude shorter than the Hubble time, and significantly shorter than the ages of galactic disks.

As a consequence, without a sustaining mechanism, any large-scale primordial or protogalactic magnetic field would be expected to decay exponentially on timescales far shorter than a galaxy’s lifetime (e.g. [Beck, 2015](#); [Shukurov & Subramanian, 2021](#)). More generally, explaining galactic magnetism involves two related but distinct requirements: preserving large-scale coherence against turbulent diffusion, and reaching the observed magnetic-energy content starting from weak seed fields. While the long-term coherence of a large-scale field may be facilitated by a mitigation of turbulent diffusion and by large-scale transport processes such as magnetic helicity fluxes and vertical advection (e.g. [Chatterjee et al., 2011](#); [Shukurov et al., 2006](#)), explaining the observed magnetic-energy content requires an efficient conversion of kinetic energy into magnetic energy ([Brandenburg & Subramanian, 2005](#); [Brandenburg & Ntormousi, 2023](#)).

Several mechanisms have been proposed for the origin of cosmic seed magnetic fields. These include primordial fields generated during inflation or cosmological phase transitions; plasma instabilities such as the Weibel instability at shocks; and battery effects such as the Biermann battery, which operate in regions with misaligned density and pressure gradients. These processes typically yield field strengths in the range $10^{-20}\text{--}10^{-12}$ G, depending on the scenario. Such values are orders of magnitude below the μG -level fields observed in present-day galaxies, and cannot by themselves explain their persistence over cosmic timescales without subsequent amplification by galactic dynamos ([Kulsrud & Zweibel, 2008](#); [Durrer & Neronov, 2013](#); [Subramanian, 2016](#)).

Reconciling the observed longevity of galactic magnetic fields with their natural tendency to decay has been a central motivation for the development of dynamo theory, the leading framework for explaining the in-situ amplification and maintenance of astrophysical magnetic fields. Dynamo theory encompasses a class of processes that convert kinetic energy from galactic motions into magnetic energy, enabling exponential field growth that compensates for turbulent losses.

Two complementary dynamo mechanisms are thought to operate in galaxies:

1. The **large-scale (mean-field) dynamo**, often described as the α – Ω dynamo, which relies on the interplay between differential rotation and helical turbulence to amplify and order fields on scales comparable to the galactic disk. This mechanism is capable of generating coherent, spiral-like magnetic patterns consistent with those observed in disk galaxies (see [Brandenburg & Subramanian, 2005](#) for a recent theoretical review and [Beck, 2015](#) for an observational one).
2. The **small-scale (fluctuation) dynamo**, which acts locally and stochastically by stretching and folding field lines through random turbulent motions. It can rapidly amplify very weak seed fields on the outer scale of turbulence and below, reaching near-equipartition strengths within tens of Myr ([Schleicher & Beck, 2013](#); [Schober et al., 2013](#)).

The small-scale dynamo provides a rapid build-up of magnetic energy, while the large-scale dynamo gradually organises the field into coherent structures over longer timescales. Their interplay is crucial for understanding the magnetic properties of spiral and starburst galaxies, where both tangled and ordered components are observed simultaneously.

In the following, we provide a theoretical overview of the physical principles and mathematical formulations underlying both large-scale and small-scale dynamos. This sets the stage for the cosmological MHD simulations discussed in Chapter 5.

1.2 Large-scale (mean-field) dynamo

The large-scale dynamo (LSD) operates in a conducting fluid subject to global rotation and turbulence with net helicity. The evolution of the mean magnetic field $\langle \mathbf{B} \rangle$ obeys the mean-field induction equation:

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \underbrace{\nabla \times (\mathbf{V} \times \langle \mathbf{B} \rangle)}_{\text{induction (shear/rotation)}} + \underbrace{\nabla \times (\alpha \langle \mathbf{B} \rangle)}_{\alpha\text{-effect (gain)}} + \underbrace{\eta_t \nabla^2 \langle \mathbf{B} \rangle}_{\text{turbulent diffusion (loss)}} \quad (1.2)$$

Where $\mathbf{V} \equiv \langle \mathbf{V} \rangle$ is the large-scale (mean) flow, dominated by differential rotation $\Omega(R)$ as a function of the galactocentric radius R . The parameter α is given by $\alpha \simeq -\frac{\tau_c}{3} \langle \mathbf{u} \cdot (\nabla \times \mathbf{u}) \rangle$, with τ_c the correlation time and $\mathbf{u}$ the turbulent velocity. η_t is the turbulent magnetic diffusivity, $\eta_t \simeq \frac{1}{3} u_{\text{turb}} \ell_{\text{turb}}$.

The LSD is often referred to as the α – Ω dynamo ([Beck et al., 1996](#)). We can distinguish in Equation 1.2 these different effects:

- **Ω -effect (induction):** shear converts poloidal field into toroidal, $\nabla \times (\mathbf{V} \times \langle \mathbf{B} \rangle)$;

- **α -effect (gain):** helical turbulence regenerates poloidal field from toroidal, $\nabla \times (\alpha \langle \mathbf{B} \rangle)$;
- **Diffusion (loss):** turbulent decay and scale setting, $\eta_t \nabla^2 \langle \mathbf{B} \rangle$ (for uniform η_t).

The growth rate of the large-scale dynamo is set by the balance between field amplification through the α - Ω mechanism and turbulent diffusion.

The characteristic exponential growth time of the mean-field dynamo is of the order of the turbulent diffusion time across the disc, $t_{\text{diff}} \sim h^2/\eta_t$ (see Section 1.1), yielding typical values of ~ 0.1 – 1 Gyr for standard galactic disc parameters (e.g. Beck, 2015; Shukurov & Subramanian, 2021). Saturation occurs when the back-reaction of the magnetic field on the turbulent flow limits further amplification. In practice, this happens when the large-scale field strength approaches a fraction of the turbulent equipartition field, defined by equating magnetic and turbulent kinetic energy densities:

$$B_{\text{eq}} \equiv \sqrt{4\pi\rho} v_{\text{turb}}. \quad (1.3)$$

Where ρ is the gas volume density. For Milky-Way-like parameters ($\rho \sim 10^{-24} \text{ g cm}^{-3}$, $v_{\text{turb}} \sim 10 \text{ km s}^{-1}$, Beck, 2015; Draine, 2011; Tamburro et al., 2009; Ferrière, 2001), this corresponds to $B_{\text{eq}} \sim 1$ – $10 \mu\text{G}$, in excellent agreement with observed field strengths (Beck, 2015; Beck et al., 2019).

It is worth noting that the LSD does not necessarily saturate at full equipartition with turbulence. Numerical simulations suggest that the ordered component of the field typically reaches a fraction (of order tens of percent) of B_{eq} , with the remainder residing in the tangled small-scale component generated by the fluctuation dynamo (Brandenburg & Subramanian, 2005). The relative balance between these components depends sensitively on the star formation rate, the disk thickness, and the efficiency of helicity removal by galactic outflows.

A central issue in mean-field dynamo theory is the problem of α -quenching. As the large-scale field grows, it generates magnetic helicity of opposite sign at small scales. This small-scale helicity acts to suppress the α -effect, effectively inhibiting further amplification if it accumulates. In closed systems, this leads to premature saturation well below equipartition. However, real galaxies are not closed: galactic winds, fountain flows, and diffusive fluxes can transport small-scale helicity out of the dynamo-active region, thereby alleviating α -quenching and allowing the LSD to operate efficiently over Gyr timescales (e.g. Shukurov & Subramanian, 2021). If outflows are too weak, the accumulated small-scale helicity quenches the α -effect; if they are too strong, the mean magnetic field is advected out of the disk before it can be amplified. This competition

implies an optimal range of outflow strengths in which the α - Ω dynamo operates most efficiently, sustaining large-scale fields over galactic timescales (Rodrigues et al., 2015). In typical disk galaxies, galactic outflows are predicted to be strongest above the gaseous spiral arms, leading to more efficient α - Ω dynamo action (via better small-scale helicity removal with less large-scale field advection) in the interarm regions (Chamandy et al., 2015). However, in systems with intense nuclear starbursts, much stronger central outflows can dominate

Large-scale dynamos leave clear observational imprints that distinguish them from purely turbulent fields. The most direct tracer is the presence of coherent Faraday rotation measure (RM, see Section 2.2) patterns across galactic disks, often revealing large-scale field modes with azimuthal symmetries (e.g. axisymmetric or bisymmetric). In synchrotron and FIR polarisation maps, mean-field dynamos naturally explain the ordered, spiral-shaped polarisation vectors that follow the stellar arms but with characteristic pitch angles that differ from those of the gaseous arms, reflecting the balance between shear and turbulent helicity (Beck, 2015; Borlaff et al., 2023).

In edge-on galaxies, dynamo-generated fields extend vertically into the halo. Observations frequently show *X-shaped* magnetic structures above and below the disk plane (see Section 2.3.1), with polarisation vectors opening away from the midplane (Heesen et al., 2009, 2011; Belfiori et al., 2025). Such morphologies are a natural outcome of wind-disk coupling: large-scale outflows advect the dynamo-generated fields into the halo while simultaneously providing the helicity flux needed to alleviate α -quenching (Beck et al., 1996, 2019). These observational features together constitute strong evidence that large-scale dynamo action operates efficiently in disk galaxies over cosmic timescales.

In this context, observations of nearby starburst galaxies such as NGC 253 are particularly valuable: the high turbulence and powerful outflows of these galaxies create ideal conditions for both dynamo amplification and helicity transport. We will return to this case in Chapter 3, where observational evidence for strong, ordered fields in the central regions is analysed in detail.

1.3 Small-scale (fluctuation) dynamo

The small-scale dynamo (SSD) amplifies magnetic fields through the random stretching, twisting, and folding of field lines by turbulent motions in the ISM. Unlike the large-scale dynamo, it does not rely on differential rotation or net helicity; it is a generic outcome of turbulence in a conducting plasma. The SSD operates on short timescales, typically comparable to the eddy turnover time, and can therefore rapidly boost weak seed fields

to dynamically relevant strengths (e.g. Schleicher & Beck, 2013; Schober et al., 2013).

In the kinematic phase, when magnetic back-reaction is negligible, the magnetic energy U_B grows exponentially,

$$U_B(t) \propto U_{B,0} \exp(\Gamma t), \quad (1.4)$$

with growth rate Γ determined by the properties of the turbulent flow. Kazantsev theory describes the time evolution of the magnetic energy that grows due to turbulent motions of a conducting fluid (Kazantsev, 1968). It shows that the fastest amplification occurs near the smallest dynamically active eddies, giving:

$$\Gamma \sim \frac{v_{\text{turb}}}{L}$$

where v_{turb} is the turbulent rms velocity at the forcing (injection) scale L (Kazantsev, 1968; Kulsrud & Anderson, 1992; Brandenburg & Subramanian, 2005; Schober et al., 2012, 2013; Schleicher & Beck, 2013).

For disk-like conditions one typically has $v_{\text{turb}} \sim 5\text{--}10 \text{ km s}^{-1}$ and $L \sim 50\text{--}100 \text{ pc}$, so the eddy turnover time is

$$t_{\text{eddy}} \equiv \frac{L}{v_{\text{turb}}} \sim 5\text{--}20 \text{ Myr},$$

so many e-foldings can occur within a single star-formation episode ($\sim 10\text{--}100 \text{ Myr}$).

Once the Lorentz force becomes important, the SSD enters a nonlinear regime where growth slows and the magnetic spectrum shifts toward larger scales. Saturation occurs when magnetic energy reaches a fraction of the turbulent kinetic energy,

$$B_{\text{sat}} = \sqrt{f_{\text{sat}} 4\pi\rho} v_{\text{turb}}, \quad (1.5)$$

with $f_{\text{sat}} \sim 0.05\text{--}0.5$ depending on forcing and plasma parameters (Brandenburg & Subramanian, 2005; Schober et al., 2013). Under Milky Way conditions this yields B_{sat} of a few μG , while in starburst nuclei higher gas densities and turbulent velocities drive saturation values of tens-hundreds of μG (Lacki & Beck, 2013; Lopez-Rodriguez et al., 2021).

The SSD generates tangled fields with coherence scales of the order of the turbulent driving length and strong spatial intermittency. This leads to depolarisation and patchy polarised emission in galaxies, as well as significant fluctuations in Faraday rotation measures. Such signatures are particularly relevant in central starbursts like NGC 253, where high turbulence and gas density favour rapid SSD amplification. Resolving these

small-scale magnetic structures requires high-resolution, multi-frequency polarimetric observations, which can capture the characteristic fluctuations in both polarised intensity and Faraday rotation. We return to this case in Chapter 3.

In practice, both small- and large-scale dynamos operate together. The SSD rapidly amplifies the total magnetic energy, while the large-scale dynamo gradually organises part of this energy into coherent structures on longer timescales. Galactic outflows can transport SSD-amplified fields into the halo and facilitate the removal of small-scale helicity, thereby supporting the growth of ordered fields (Shukurov et al., 2006). This interplay between fluctuation and mean-field processes is an essential ingredient in the magnetisation of galaxies.

1.4 Scaling relations between star formation and magnetic fields

Magnetic fields in galaxies are observed to correlate with measures of star formation activity, both locally within galactic disks and in global, integrated quantities. Systems with higher star formation rates tend to host stronger magnetic fields, with values ranging from a few μG in quiescent spirals to tens of μG in nuclear starbursts and ultraluminous infrared galaxies (Niklas & Beck, 1997; Chyży et al., 2011; Lacki & Beck, 2013; Heesen et al., 2023).

This B-star formation connection underpins the tight correlation between FIR and Radio continuum (RC) in star-forming galaxies, from normal spirals to starbursts (Figure 1.1; Yun et al., 2001). This RC–FIR link extends to the molecular ISM: both global and spatially resolved studies show strong correlations between RC and CO emission in nearby galaxies, with nearly constant RC/CO ratios within and across disks (Murgia et al., 2002, 2005; Paladino et al., 2006, 2008).

These RC–FIR and RC–molecular trends support the idea that stellar feedback and the star-formation cycle regulate cosmic-ray electrons and magnetic fields, pointing to a physical mechanism linking star formation and magnetic fields. A natural explanation for this link is that turbulence injected by stellar feedback drives dynamo action in the ISM. If the field is frozen into the gas, one expects a generic density scaling $B \propto \rho^\kappa$, where κ depends on geometry and conditions (e.g. $\kappa = 2/3$ for isotropic compression; $\kappa = 0$ – 1 for shocks depending on field orientation; Mestel & Paris 1984; Van Eck et al. 2015).

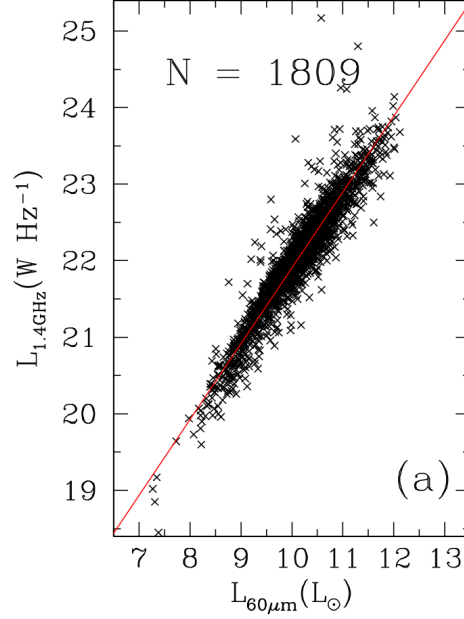


Figure 1.1. Correlation between 1.4 GHz radio luminosity and IRAS 60 μm luminosity for star-forming galaxies. Each point represents a galaxy, and the red line shows a linear relation with a constant offset, illustrating the tightness of the radio–FIR correlation across more than four orders of magnitude in luminosity. Image adapted from [Yun et al., 2001](#)

SN injection–dissipation with saturated SSD. At dynamo saturation, the magnetic energy density is a fixed fraction of the turbulent kinetic energy,

$$\frac{B^2}{8\pi} = f_{\text{sat}} \frac{1}{2} \rho v_{\text{turb}}^2, \quad (1.6)$$

where B is the total magnetic field strength, ρ the mean mass density, v_{turb} the three-dimensional rms turbulent velocity, and f_{sat} the saturation fraction of the small-scale dynamo ([Brandenburg & Subramanian, 2005](#); [Schober et al., 2013](#)). Supernovae inject turbulent energy at a rate per unit area that scales with the star-formation rate surface density,

$$\Sigma_{\text{inj}} \propto \Sigma_{\text{SFR}}.$$

Turbulent dissipation proceeds on an eddy timescale $t_{\text{diss}} \simeq L/v_{\text{turb}}$. The turbulent energy per unit area is approximately $\frac{1}{2} \Sigma_{\text{gas}} v_{\text{turb}}^2$, and in steady state this energy is dissipated at a rate per unit area of $\sim \frac{\frac{1}{2} \Sigma_{\text{gas}} v_{\text{turb}}^2}{t_{\text{diss}}} \propto \Sigma_{\text{gas}} v_{\text{turb}}^3 / L$, which must balance the injection rate $\Sigma_{\text{inj}} \propto \Sigma_{\text{SFR}}$. Balancing injection and dissipation per unit area therefore

gives

$$\frac{\frac{1}{2} \Sigma_{\text{gas}} v_{\text{turb}}^2}{t_{\text{diss}}} \propto \Sigma_{\text{inj}} \quad \Rightarrow \quad v_{\text{turb}}^3 \propto \frac{L \Sigma_{\text{SFR}}}{\Sigma_{\text{gas}}},$$

where Σ_{gas} is the gas surface density. Assuming the driving scale follows the disc thickness, $L \propto h$, and using $\rho \simeq \Sigma_{\text{gas}}/(2h)$, we obtain

$$v_{\text{turb}} \propto \left(\frac{\Sigma_{\text{SFR}}}{\rho} \right)^{1/3}.$$

Substituting into Eq. (1.6) gives the saturated field (up to order-unity factors):

$$B_{\text{sat}} \propto \rho^{1/2} v_{\text{turb}} \propto \Sigma_{\text{SFR}}^{1/3} \rho^{1/6}.$$

If ρ (or h) varies weakly across the galaxy sample, this reduces to the robust scaling

$$B \propto \Sigma_{\text{SFR}}^{1/3},$$

consistent with analytic expectations and numerical studies of SN-driven turbulence and small-scale dynamos (Schleicher & Beck, 2013; Lacki & Beck, 2013).

The B - Σ_{SFR} relation can also be formulated in terms of global galaxy properties, replacing surface densities with integrated quantities. Assuming a roughly constant disk scale height h across a galaxy sample, one can relate the Σ_{SFR} to the SFR via $\Sigma_{\text{SFR}} \simeq \text{SFR}/(\pi R^2)$, where R is the effective star-forming radius of the disk. Combining this with the scaling $B \propto \Sigma_{\text{SFR}}^{1/3}$ yields

$$B \propto \left(\frac{\text{SFR}}{R^2} \right)^{1/3}. \quad (1.7)$$

If R varies only weakly with SFR across the galaxy population, this relation simplifies to a power law $B \propto \text{SFR}^{1/3}$, consistent with observational determinations of the global B -SFR relation (e.g. Chyży et al., 2011; Van Eck et al., 2015).

This integrated form is particularly useful when comparing entire galaxies, either in surveys or in simulations where global magnetic energies and star formation rates are measured. Observationally, the correlation has been detected over several orders of magnitude in SFR, with slopes $\alpha \approx 0.2$ – 0.4 (Niklas & Beck, 1997; Chyży et al., 2011; Heesen et al., 2023). In high-SFR systems such as ULIRGs or nuclear starbursts (e.g. NGC 253, M 82), the integrated relation naturally extends to field strengths of 50–100 μG , consistent with expectations from turbulent equipartition in dense, supernova-driven ISM environments (Lacki & Beck, 2013; Lopez-Rodriguez, 2023). From a theoretical

standpoint, this formulation emphasises that the integrated SFR is not a fundamental driver on its own, but rather a tracer of the global turbulence budget in a galaxy. The effective coupling arises because both star formation and magnetic field amplification are regulated by the available gas reservoir and the efficiency of supernova feedback in driving turbulence.

As shown so far, the connection between star formation and magnetic fields holds both locally, within galactic disks, and globally, under the assumption of disk sizes and scale heights. This duality is especially relevant for numerical simulations and case studies of individual galaxies, where both integrated properties and resolved disk regions can be analysed. In this thesis we will use both quantities to analyse how magnetic field amplification is related with star formation activity and energy balance in galactic disks and outflows in a sample of simulated galaxies (See Chapter 5).

1.5 Magnetic energy and the interstellar medium energy budget

Once amplified to μG strengths, magnetic fields reach energy densities comparable to those of turbulence, thermal gas, and cosmic rays in the ISM. As a result, they play a fundamental role in shaping the ISM and driving galactic evolution (Beck, 2015).

The magnetic, turbulent, and thermal energy densities are

$$U_B = \frac{B^2}{8\pi}, \quad U_{\text{turb}} = \frac{1}{2}\rho v_{\text{turb}}^2, \quad U_{\text{th}} = \frac{3}{2}nk_{\text{B}}T,$$

where n is the number density, ρ the gas density, T the gas temperature, and k_{B} Boltzmann's constant. Cosmic rays contribute an energy density U_{CR} that is often near equipartition with U_B in disk galaxies (Beck & Krause, 2005; Beck, 2015).

For Milky Way-like conditions ($B \sim 5 \mu\text{G}$, $n \sim 1 \text{ cm}^{-3}$, $v_{\text{turb}} \sim 10 \text{ km s}^{-1}$, $T \sim 10^4 \text{ K}$), one finds each component is $\sim 10^{-12} \text{ erg cm}^{-3}$ (e.g. Draine, 2011; Basu & Roy, 2013; Beck, 2015). This near-equipartition is naturally expected once dynamos saturate and supernova feedback regulates midplane pressure.

We can quantify the relative importance with pressure (or energy) ratios:

$$\beta_{\text{th}} \equiv \frac{P_{\text{th}}}{P_B} = \frac{nk_{\text{B}}T}{B^2/8\pi} = \frac{2}{3} \frac{U_{\text{th}}}{U_B},$$

$$\beta'_{\text{turb}} \equiv \frac{U_{\text{turb}}}{U_B} = \frac{\frac{1}{2}\rho v_{\text{turb}}^2}{B^2/8\pi} = \left(\frac{v_{\text{turb}}}{v_A} \right)^2 \equiv \mathcal{M}_A^2,$$

where $P_B = U_B$ is the magnetic pressure, $v_A = B/\sqrt{4\pi\rho}$ is the Alfvén speed, and $\mathcal{M}_A$ the Alfvénic Mach number. For (nearly) isothermal gas, the thermal beta can also be written

$$\beta_{\text{th}} \simeq 2 \frac{c_s^2}{v_A^2} = 2 \frac{\mathcal{M}_A^2}{\mathcal{M}_s^2},$$

with sound speed c_s and sonic Mach number $\mathcal{M}_s = v_{\text{turb}}/c_s$ (Kulsrud, 2004; Brandenburg & Subramanian, 2005; Draine, 2011). Values $\mathcal{M}_A > 1$ indicate super-Alfvénic turbulence (hence turbulence dominated), while $\mathcal{M}_A < 1$ corresponds to sub-Alfvénic regimes (turbulence is magnetically dominated) (Krumholz & Federrath, 2019; Federrath, 2016).

β_{th} captures phase-dependent thermal vs. magnetic support, while β'_{turb} (energy ratio) tracks how close the turbulence is to Alfvénic. In disks, both are typically ~ 1 ; in dense gas, $\beta_{\text{th}} \ll 1$; and in starburst nuclei, both magnetic and turbulent pressures are comparably important, with cosmic rays adding another $\sim$ equipartition component (Beck, 2015).

β'_{turb} and M_A are useful diagnostics that connect directly to simulation and observational measures. Magnetic fields mediate anisotropic CR transport, and the balance among CR, thermal, turbulent and magnetic pressures shapes wind dynamics—CR pressure can help launch and sustain outflows under plausible conditions (Everett et al., 2008; Hopkins et al., 2020).

In contrast to the near-equipartition conditions typical of galactic disks, the nearby starburst galaxy NGC 253 provides a clear example of a magnetically dominated environment. Radio observations indicate central magnetic field strengths of $B \sim 50\text{--}100\,\mu\text{G}$ (Heesen et al., 2009; Adebahr et al., 2013), far exceeding typical disk values. This implies $\beta_{\text{th}} < 1$ in the starburst nucleus, where magnetic and cosmic-ray pressures dominate over thermal gas pressure (Heesen et al., 2011; Beck, 2015). Such conditions suggest that the magnetic field is not merely a passive tracer of turbulence, but actively regulates the ISM, collimates the multiphase outflows, and mediates cosmic-ray transport. These findings make NGC 253 one of the best local laboratories for studying magnetically-influenced galactic outflows. In turbulence-dominated regimes, on the contrary, the field behaves more like a passive tracer than a regulating agent.

This near-equipartition sets the physical stage for the analysis presented in Chapter 5, where we quantify magnetic, turbulent, and thermal energies in simulated galaxies and examine their relation with star formation.

1.6 Magnetised galactic outflows and their connection to star formation

Stellar feedback in the form of supernova explosions, stellar winds, and radiation pressure can drive large-scale outflows that advect magnetic flux and cosmic rays out of the disk, magnetising the circumgalactic medium (CGM) and building radio halos (e.g. [Heesen et al., 2009](#); [Beck, 2015](#)).

As discussed in Section 1.2, outflows are also central to large-scale dynamo theory. Once magnetic fields are amplified in the disk, galactic winds can transport them vertically into the halo. This process helps to alleviate α -quenching: small-scale magnetic helicity, which would otherwise suppress further dynamo growth, can be transported out of the disk, allowing the mean-field dynamo to operate efficiently over Gyr timescales ([Shukurov & Subramanian, 2021](#)). The X-shaped magnetic structures seen in edge-on galaxies such as NGC 253, NGC 891, and M 82 are widely interpreted as signatures of this coupling between disk dynamos and vertical advection into the halo ([Heesen et al., 2011](#); [Beck, 2015](#); [Belfiori et al., 2025](#)).

NGC 253 stands out as a nearby nuclear starburst galaxy hosting a well-characterised magnetised outflow. Radio polarisation maps reveal vertically oriented, filamentary magnetic structures forming an X-shaped halo that extends to at least a kiloparsec above the disk ([Heesen et al., 2009, 2011](#)). In the outflow cones, equipartition estimates give a total field of $B_{\text{tot}} \simeq 40\text{--}50\,\mu\text{G}$ and an ordered component of $B_{\text{ord}} \simeq 20\,\mu\text{G}$ ([Heesen et al., 2011](#)), values that are exceptionally high for galactic halos. The observed vertical/helical geometry—anchored in the disc and traced into the halo—is consistent with transport by the starburst-driven wind, with local compression in the cone walls enhancing the ordered field, rather than requiring a separate in-situ halo dynamo ([Heesen et al., 2009, 2011](#); [Beck, 2015](#)).

Beyond individual galaxies, magnetised outflows are thought to play a major role in enriching halos and the intergalactic medium (IGM). FIR polarimetry at low resolution directly resolves ordered magnetic fields in starburst outflows (M 82, NGC 253, NGC 2146) and shows that the polarised outflow extends to $\sim 0.3\text{--}4\,\text{kpc}$ ([Lopez-Rodriguez et al. 2021, 2023](#)). Moreover, the maximum vertical extent correlates with global SFR, linking disk star formation to halo magnetisation ([Lopez-Rodriguez, 2023](#)). Energy-budget estimates further indicate that turbulent and magnetic energies are of comparable order in the central $\sim\text{kpc}$ ($\beta'_{\text{turb}} \sim 1\text{--}30$), consistent with winds advecting dynamically important fields into the CGM ([Lopez-Rodriguez et al. 2021, 2023](#)).

Surveys of edge-on galaxies likewise reveal extended radio halos commonly interpreted

as the magnetised imprint of star-formation-driven winds (Krause et al., 2018; Heesen et al., 2018; Stein et al., 2019; Mora-Partiarroyo et al., 2019; Heald et al., 2022).

Cosmological and high-resolution ISM simulations consistently highlight the role of winds and outflows in driving galactic and circumgalactic magnetisation. Local shearing-box models show exponential mean-field growth, with inward turbulent pumping approximately balanced by outflowing winds (Gressel et al., 2008), while cosmological zoom simulations reproduce the same two-stage picture: rapid SSD amplification followed by the advection of magnetic fields into the CGM (Rieder & Teyssier, 2017). In this scenario, supernova-driven turbulence first amplifies weak seed fields through a small-scale dynamo in the disk, after which the resulting magnetic flux is transported into the halo by galactic fountains and winds.

On halo scales, MHD simulations find that before $z \sim 1$ the CGM becomes magnetised primarily by outflows from the disk rather than by in-situ amplification: winds carry ISM magnetic fields to tens of kiloparsecs, imprinting coherent, open field geometries and building up U_B of an order-of-magnitude of the U_{turb} near the disk (Pakmor et al., 2020). This simulated picture aligns with observational constraints on magnetised halos from background-source Faraday rotation and stacked analyses, which infer CGM fields declining slowly with radius and consistent with outflow seeding (Lan & Prochaska, 2020; Heesen et al., 2023).

MHD simulations which include cosmic rays transport give further evidence of the connection between star formation and halo magnetisation: they show that anisotropic CR diffusion/streaming launches bipolar winds that more efficiently advect magnetic fields into the CGM and can modify disk amplification if diffusion is treated isotropically (Pakmor et al., 2016).

In summary, galactic outflows transport dynamo-amplified fields from disks into halos, regulate large-scale dynamo saturation by removing helicity, and ensure that the CGM becomes magnetised.

I

Observational Framework

2

Observational tracers of galactic magnetic fields

In this chapter we review how magnetic fields are inferred from polarimetric measurements from Radio to FIR. We begin with the essential definitions of polarimetry in Section 2.1, introducing the Stokes parameters, linear polarisation fraction, and the electric-vector position angle, together with practical aspects such as noise bias and uncertainty propagation.

We then survey the principal observational tracers in Section 2.2, distinguishing between radio synchrotron emission and far-IR/submm thermal emission from aligned dust grains. Section 2.3 focuses on synchrotron emission in the radio regime, which probes magnetic fields in the warm, diffuse interstellar medium; we discuss spectra, polarisation, equipartition field estimates, and applications to galactic disks and halos. In Section 2.4 we review thermal dust polarisation, which accesses magnetic fields in colder, denser regions; we outline the physics of grain alignment (RATs), the polarised SED, and field-strength estimators.

In Section 2.5 reviews dust-polarisation results in Galactic and extragalactic environments (e.g. Planck, SALSA and ALMA), highlighting how geometry, turbulence, and alignment efficiency shape the observed polarisation. Appendix A2 briefly introduces ALMA’s full-polarisation capabilities and the essentials of interferometric polarisation calibration. These elements provide the observational context for our ALMA analysis of NGC 253 in Chapter 3.

2.1 Polarimetry definitions

Electromagnetic waves can be described as non-zero solutions of Maxwell’s equations in vacuum. A monochromatic plane wave propagates along the $+z$ direction with angular frequency ω and wavenumber $k = \omega/c$. At the reference plane $z = 0$, its transverse electric field can be expressed in Euclidean coordinates (x, y, z) as

$$E_x(t) = E_x(0) \cos(\omega t - \phi_1), \quad (2.1)$$

$$E_y(t) = E_y(0) \cos(\omega t - \phi_2), \quad (2.2)$$

where $E_x(0)$ and $E_y(0)$ denote the (time-independent) amplitudes at $z = 0$, and $\phi_{1,2}$ are phases.

In general, the tip of the electric field vector traces an ellipse in the xy plane (see left panel of Figure 2.1); the wave is therefore elliptically polarised. The orientation of the ellipse is time-independent, and the polarisation angle χ is defined as the counterclockwise angle from the $+x$ axis to the semi-major axis of the ellipse. Elliptical polarisation represents the most general state: linear polarisation corresponds to the degenerate case in which the ellipse collapses to a line, while circular polarisation is the opposite limit where the ellipse becomes a circle.

In astronomical observations, radiation is measured through intensities rather than field amplitudes; it is therefore convenient to quantify polarisation in terms of characteristic intensity components, called Stokes parameters (defined in [Stokes, 1851](#)):

$$\begin{aligned} I &= \langle E_x^2 + E_y^2 \rangle, \\ Q &= \langle E_x^2 - E_y^2 \rangle, \\ U &= \langle 2E_x E_y \cos \delta \rangle, \\ V &= \langle 2E_x E_y \sin \delta \rangle, \end{aligned} \tag{2.3}$$

where δ is $\phi_2 - \phi_1$ and $\langle \rangle$ a time average over many wave periods.

By definition, I represents the total intensity of the wave. The parameter Q measures the difference in intensity between the x and y components. The parameter U describes the difference between field components oriented at 45° and 135° with respect to the positive x axis. Together, Q and U track the degree of linear polarisation.

Finally, the parameter V corresponds to the intensity of circularly polarised light. The fundamental polarisation geometries are illustrated in the right panel of Figure 2.1.

From the linear Stokes parameters, the (linear) polarised intensity and the fractional linear polarisation are

$$PI \equiv \sqrt{Q^2 + U^2}, \quad PF \equiv \frac{PI}{I} = \frac{\sqrt{Q^2 + U^2}}{I}. \tag{2.4}$$

The electric-vector position angle χ of linear polarisation is

$$\chi \equiv \frac{1}{2} \operatorname{atan2}(U, Q), \tag{2.5}$$

where $\operatorname{atan2}(U, Q)$ is the two-argument arctangent that returns the correct quadrant; by definition χ is defined modulo 180° (or π radians).

The notation used in this section derives from [Trippe, 2014](#).

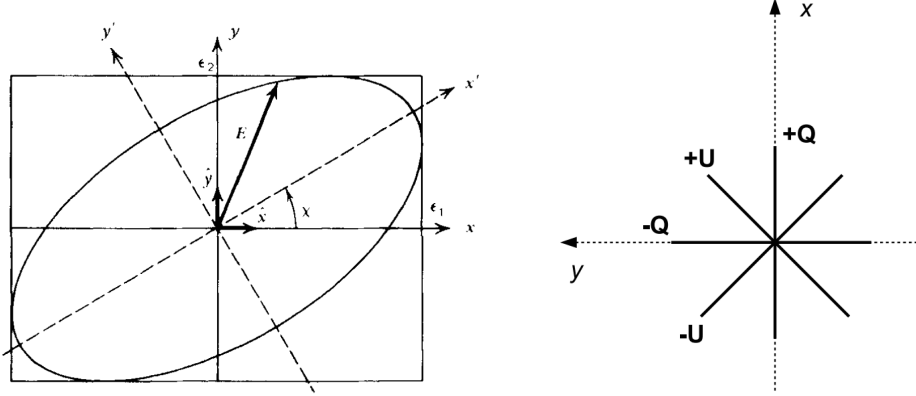


Figure 2.1. *Left panel:* Geometry of an elliptically polarised wave. The electric field vector $\mathbf{E}$ rotates in time tracing an ellipse in the transverse (x, y) plane. The quantities ϵ_1 and ϵ_2 represent the instantaneous components of $\mathbf{E}$ along the x and y axes. The polarisation angle χ defines the orientation of the semi-major axis with respect to the x axis. Image from [Rybicki & Lightman \(1986\)](#). *Right panel:* Coordinates and geometries of the Stokes parameters. Figure adapted from [Trippe, 2014](#).

Noise bias and uncertainties

In polarimetric measurements, noise in the Stokes parameters Q , U , and I introduces biases and uncertainties in derived quantities like PI, PF, and χ . The polarised intensity, $PI = \sqrt{Q^2 + U^2}$, is nonlinear and constrained to be non-negative, leading to an upward bias ([Wardle & Kronberg, 1974](#); [Vaillancourt, 2006](#)).

For the common case of independent, equal-variance noise in Q and U ($\sigma_Q = \sigma_U = \sigma$, $\text{Cov}(Q, U) = 0$), the approximate 1σ uncertainties are:

$$\sigma_{PI} \approx \sigma, \quad (2.6)$$

$$\sigma_{PF} \approx \frac{1}{I} \sqrt{\sigma_{PI}^2 + PF^2 \sigma_I^2}, \quad (2.7)$$

$$\sigma_\chi \approx \frac{1}{2} \frac{\sigma_{PI}}{PI} \quad (\text{in radians, valid for } PI/\sigma_{PI} \gtrsim 3), \quad (2.8)$$

where σ_I is the uncertainty in the total intensity I . As a rule of thumb, a signal-to-noise ratio of $PI/\sigma_{PI} = 3$ corresponds to an uncertainty of approximately 10° on χ , while $PI/\sigma_{PI} = 10$ yields roughly 3° ([Naghizadeh-Khouei & Clarke, 1993](#)).

In real observations, Q , U , and I may be correlated due to factors like mapmaking, calibration, or beam smoothing. To account for these correlations, uncertainties can be

computed using the full covariance matrix:

$$\Sigma = \begin{bmatrix} \sigma_{II} & \sigma_{IQ} & \sigma_{IU} \\ \sigma_{IQ} & \sigma_{QQ} & \sigma_{QU} \\ \sigma_{IU} & \sigma_{QU} & \sigma_{UU} \end{bmatrix}, \quad (2.9)$$

neglecting Stokes V . Following [Montier et al., 2015a](#), the uncertainties are:

$$\sigma_{PI}^2 = \frac{Q^2\sigma_{QQ} + U^2\sigma_{UU} + 2QU\sigma_{QU}}{Q^2 + U^2}, \quad (2.10)$$

$$\sigma_{PF}^2 = \frac{1}{PF^2 I^4} \left(Q^2\sigma_{QQ} + U^2\sigma_{UU} + 2QU\sigma_{QU} - 2IQPF^2\sigma_{IQ} - 2IUPF^2\sigma_{IU} + PF^4 I^2\sigma_{II} \right), \quad (2.11)$$

$$\sigma_\chi^2 = \frac{1}{4} \frac{Q^2\sigma_{UU} + U^2\sigma_{QQ} - 2QU\sigma_{QU}}{(Q^2 + U^2)^2} \quad (\text{in radians}). \quad (2.12)$$

To correct for the bias, the following debiased estimators are used for high S/N ($PI/\sigma_{PI} \gtrsim 3$):

$$\hat{PI} \approx \sqrt{PI^2 - \sigma_{PI}^2}, \quad \hat{PF} \approx \sqrt{PF^2 - \sigma_{PF}^2}, \quad (2.13)$$

where σ_{PI}^2 and σ_{PF}^2 are computed using 2.9 ([Wardle & Kronberg, 1974](#); [Vaillancourt, 2006](#); [Montier et al., 2015a](#)).

For lower S/N, the modified-asymptotic (MAS) estimator ([Montier et al., 2015b](#)) provides a more robust debiasing for PF:

$$\hat{PF}_{\text{MAS}} = PF - \frac{b^2}{2PF} \left[1 - \exp\left(-\frac{PF^2}{b^2}\right) \right], \quad (2.14)$$

where b^2 is the “noise-bias” term defined from the Q - U covariance (see [Montier et al., 2015b](#), Equation 15).

These formulations will be used in detail in our analysis of NGC 253 (see Section 3.4), where we quantify the impact of correlated noise on the derived polarisation quantities.

2.2 Main magnetic field tracers

Magnetic fields in galaxies cannot be observed directly. Instead, their properties can be analysed through their interaction with other elements of the interstellar medium (ISM) such as cosmic rays, ionised gas, and dust. Several observational techniques can be used, each sensitive to different effects of the magnetic fields.

- **Zeeman splitting** The Zeeman effect is the most direct method of probe as-

trophysical magnetic fields. In the presence of a line-of-sight magnetic field, a spectral line of rest frequency ν_0 is split into two oppositely circularly polarised components (longitudinal Zeeman effect), separated by

$$\Delta\nu = b B,$$

with b the line-dependent splitting coefficient (e.g. 2.8 Hz per μG for H I). The splitting is minute compared to typical line widths, so radio detections rely on the characteristic antisymmetric signature in the Stokes V profile. Zeeman detections in H I, OH, CN, and H_2O (including maser lines with large b) have yielded μG – mG measurements in environments from diffuse atomic gas to dense star-forming cores (Crutcher, 2012; Beck, 2015).

For fields transverse to the line of sight, the splitting produces two shifted, linearly polarised components, σ_r and σ_b plus an unshifted central line σ_π (transverse Zeeman effect). This signal is usually cancelled for unresolved lines, but detectable linear polarisation can arise if the sublevels are unequally populated due to optical depth or velocity gradients (Goldreich & Kylafis, 1981). The resulting polarisation is either parallel or perpendicular to the plane-of-sky field orientation, and has been observed in molecular clouds, star-forming regions, protostellar outflows, and supernova remnants in the Milky Way. The only robust detection so far in an external galaxy is in M33 (Li & Henning, 2011). The Zeeman effect is the only direct method for measuring magnetic field strength, yielding the line-of-sight component; other techniques infer field strengths indirectly from additional assumptions.

- **Faraday rotation** A linearly polarised wave crossing a magneto-ionic medium (as schematically shown in Figure 2.3) has its polarisation angle rotated as

$$\Delta\chi(\lambda) = \text{RM} \lambda^2,$$

where λ is in metres and the rotation measure RM (in rad m^{-2}) is

$$\text{RM} = 0.812 \int n_e (\text{cm}^{-3}) B_{\parallel} (\mu\text{G}) d\ell (\text{pc}).$$

Here n_e is the thermal electron density and $B_{\parallel}$ is the line-of-sight magnetic field; the sign of RM reflects the field direction (toward/away from the observer). Measuring RM therefore provides a direct probe of the coherent magnetic field component along the line of sight, weighted by the ionised gas. By mapping RM values across

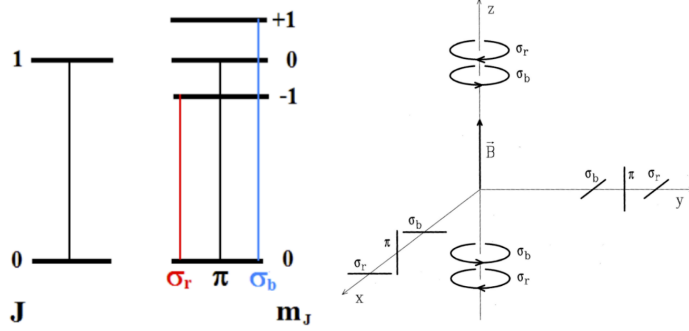


Figure 2.2. *Left panel:* Zeeman splitting of a $J = 1 \rightarrow 0$ transition in a magnetic field $\mathbf{B}$. In the absence of magnetic fields, a single line appears at ν_0 . When a magnetic field is present, the upper level splits into $m_J = +1, 0, -1$. Allowed electric-dipole transitions are $\Delta m = 0$ (unshifted π component) and $\Delta m = \pm 1$ (shifted σ components, with σ_r red-shifted and σ_b blue-shifted). Frequency separation is $\Delta\nu = bB$, with each σ line offset by $\pm\Delta\nu/2$ from ν_0 (where b is the splitting coefficient). *Right panel:* polarisations that would be observed from different angles with respect to the magnetic field. Longitudinal case (line of sight along $\mathbf{B}$, z -axis): only σ components are visible, with opposite circular polarisations. Transverse case (line of sight along y): all three lines (π , σ_r , σ_b) appear, with π linearly polarised ($\mathbf{E} \parallel \mathbf{B}$) and σ components linearly polarised ($\mathbf{E} \perp \mathbf{B}$). Axes (x, y, z) denote viewing directions. Image adapted from [Crutcher & Kemball, 2019](#)

extended sources or large samples of background sources, one can reconstruct the geometry, strength, and reversals of large-scale magnetic fields in galaxies and in the Milky Way. Deviations from the λ^2 law arise when multiple Faraday components lie along the line of sight or when internal/external depolarisation and unresolved RM gradients are present. In such cases, the broadband RM synthesis technique ([Brentjens & de Bruyn, 2005](#); [Heald, 2009](#)) allows to invert the complex polarisation as a function of λ^2 to recover the Faraday spectrum $F(\phi)$. For typical ISM conditions, Faraday rotation is strongest at decimetre wavelengths; in dense central regions it can already be significant at $\lambda \sim 1\text{--}3\text{ cm}$ ([Han, 2017](#)).

- **Synchrotron emission.** See Section 2.3 for a more detailed description of how magnetic fields can be estimated through synchrotron emission. Briefly: total intensity (Stokes I) traces the combined (ordered + random) magnetic field, while the polarisation and spectral index provide constraints on the ordered field geometry and on CR electron propagation and energy losses. Estimates of the field strength require assumptions on equipartition or on CR transport.
- **Thermal dust polarisation** See Section 2.4 for a more detailed description of how magnetic fields can be estimated through dust emission. Briefly: thermal

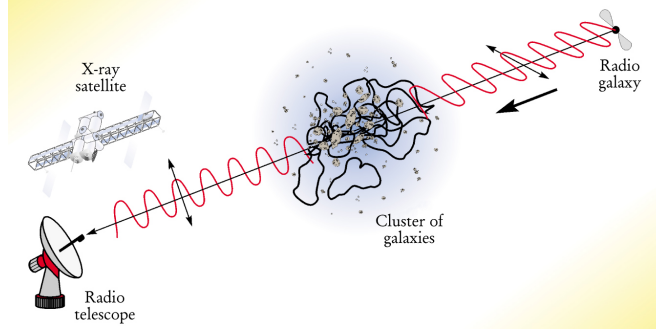


Figure 2.3. Schematic image of the Faraday rotation of the polarisation plane of background radio emission as its path traverses the intergalactic hot gas within a foreground cluster of galaxies. Image from [Kronberg, 2002](#).

emission from aspherical dust grains becomes polarised because their short (minor) axes tend to align with the local magnetic field direction. As a result, the emitted light is polarised perpendicular to the plane-of-sky component of the field. The field strength can then be estimated using dispersion-based methods, which rely on assumptions about the gas density and the level of turbulence.

This thesis focuses primarily on synchrotron and dust polarisation. Synchrotron emission is central to characterising large-scale and halo fields, as well as to quantifying magnetic energy densities in galaxy disks and outflows. Dust polarisation, on the other hand, offers a complementary view of magnetic geometries in the dense ISM and star-forming regions, where synchrotron emission may be faint or contaminated by thermal radio emission.

2.3 Synchrotron emission

Synchrotron emission is the most widely used method to study magnetic fields in galaxies. When relativistic cosmic-ray electrons (CREs), primarily accelerated in supernova remnants, diffuse into the interstellar medium, they spiral around magnetic field lines, producing diffuse radio continuum emission ([Fermi, 1949](#)). A schematic representation of the synchrotron emission process is shown in Figure 2.4.

The characteristic frequency of synchrotron radiation depends on the electron energy E and the magnetic field component perpendicular to the line-of-sight $B_{\perp}$ ([Condon, 1992](#)):

$$\left(\frac{\nu}{\text{GHz}}\right) \approx 0.016 \left(\frac{E}{\text{GeV}}\right)^2 \left(\frac{B_{\perp}}{\mu\text{G}}\right), \quad (2.15)$$

Thus, GHz-frequency radio observations trace $\sim$ GeV electrons in μ G-level fields. CREs lose energy through synchrotron radiation, giving them a finite lifetime:

$$t_{\text{syn}} \approx 1.06 \times 10^9 \text{ yr} \left(\frac{B_{\perp}}{\mu\text{G}} \right)^{-3/2} \left(\frac{\nu}{\text{GHz}} \right)^{-1/2}. \quad (2.16)$$

For typical spiral disk conditions ($B \sim 10 \mu\text{G}$, $\nu = 1 \text{ GHz}$), $t_{\text{syn}} \sim 3 \times 10^7 \text{ yr}$; in starburst nuclei ($B \sim 50 \mu\text{G}$) it drops below 1 Myr, implying that electrons must be continuously replenished by ongoing star formation.

For a CRE population with $N(E) \propto E^{-p}$, the synchrotron spectrum is $I_{\nu} \propto \nu^{-\alpha}$ with $\alpha = (p-1)/2$. Freshly shock-accelerated electrons have an injection index $p_{\text{inj}} \simeq 2.2$ ($\alpha_0 \simeq 0.6$). After synchrotron/IC cooling, radiative losses steepen the spectrum to $\alpha \sim 0.9\text{--}1.1$, i.e. $p_{\text{eff}} = 2\alpha + 1 \sim 2.8\text{--}3.2$ in the diffuse ISM (Condon, 1992; Basu et al., 2015). Spatial variations in α therefore diagnose CR transport and energy losses.

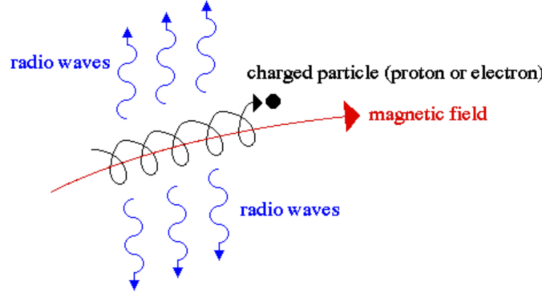


Figure 2.4. A charged particle, such as an electron or proton, spiraling along magnetic field lines undergoes centripetal acceleration, emitting electromagnetic radiation tangent to its curved trajectory. This emission combines to form a beam of synchrotron radio radiation, with its intensity and polarisation determined by the particle’s energy and the magnetic field’s component perpendicular to the line of sight. Image adapted from Rybicki & Lightman, 1986.

Because synchrotron intensity depends on both CRE density and $B_{\perp}$, field strengths are usually derived under the equipartition assumption between cosmic-ray and magnetic energy densities (Beck & Krause, 2005). This yields

$$B_{\text{eq}} \propto \left(\frac{(k+1)I_{\nu}}{L} \right)^{2/(p+5)}, \quad (2.17)$$

where k is the proton-to-electron ratio (typically assumed $k \sim 100$), L the path length and p the electron energy index.

Synchrotron emission is intrinsically linearly polarised, with a maximum degree

$$PF_{\max} = \frac{p_{\text{eff}} + 1}{p_{\text{eff}} + 7/3}, \quad (2.18)$$

where p_{eff} is the effective CRE energy index at the observing frequency (after synchrotron/IC cooling). This yields $PF_{\max} \simeq 74\%$ for $p_{\text{eff}} \simeq 2.8$. Observed polarisation fractions are lower ($\sim 5\text{--}20\%$) due to fluctuations of the magnetic field orientation within the volume traced by the telescope beam or by Faraday depolarisation (Beck, 2015). Polarisation vectors trace the ordered field component in the plane of the sky (rotated by 90° relative to the electric vector), while Faraday rotation encodes information on the line-of-sight field. Together, polarised intensity and RM mapping allow the construction of 3D models of galactic magnetic fields.

2.3.1 Applications to galactic magnetism

Synchrotron observations, combining total intensity, polarisation, and Faraday rotation data, have been indispensable in establishing many aspects of galactic magnetism:

(i) *Field strengths and energy densities.* Total synchrotron intensity, via the equipartition assumption, provides estimates of the total magnetic field strength. These reveal $B \sim 5\text{--}10 \mu\text{G}$ in the Milky Way and typical spirals, $20\text{--}30 \mu\text{G}$ in the spiral arms of more actively star-forming galaxies, and $50\text{--}100 \mu\text{G}$ in nuclear starbursts such as M 82 and NGC 253 (Beck, 2015). In the most extreme, compact ultraluminous infrared galaxies nuclei, equipartition fields can reach up to $\sim \text{mG}$ (Lacki & Beck, 2013).

(ii) *Large-scale field geometries and dynamo modes.* Polarised synchrotron emission and RM patterns have enabled the identification of coherent large-scale magnetic modes in nearby galaxies. Axisymmetric and bisymmetric configurations have been reported in systems such as M 31, M 51, and IC 342 (Fletcher et al., 2011; Beck, 2015). Figure 2.5 shows an example of an ordered magnetic field configuration for the galaxy M51. The comparison of magnetic pitch angles with gaseous spiral arms shows systematic offsets, likely due to compression/streaming in spiral arms (Van Eck et al., 2015).

(iii) *Halo fields and outflows.* Edge-on galaxies reveal extended radio halos with scale heights of several kpc. Polarisation maps frequently show X-shaped field configurations, most prominently in NGC 253, NGC 891, and M 82 (Krause, 2009; Heesen et al., 2009, 2011). These structures are interpreted as disk fields lifted into the halo by galactic winds, providing direct evidence that stellar feedback transports magnetic energy into the circumgalactic medium. Figure 2.6 shows some examples of X-shaped magnetic field configurations for edge on galaxies.

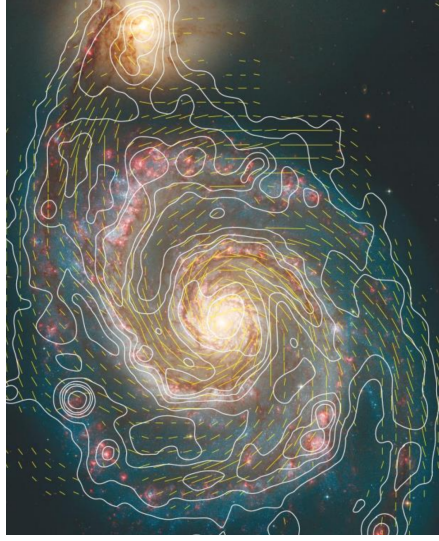


Figure 2.5. The spiral galaxy M51, showcasing total radio intensity (contours) and B-vectors at 4.86 GHz (yellow vectors), derived from combined observations using the VLA and Effelsberg 100-m telescopes. Image from [Fletcher et al., 2011](#).

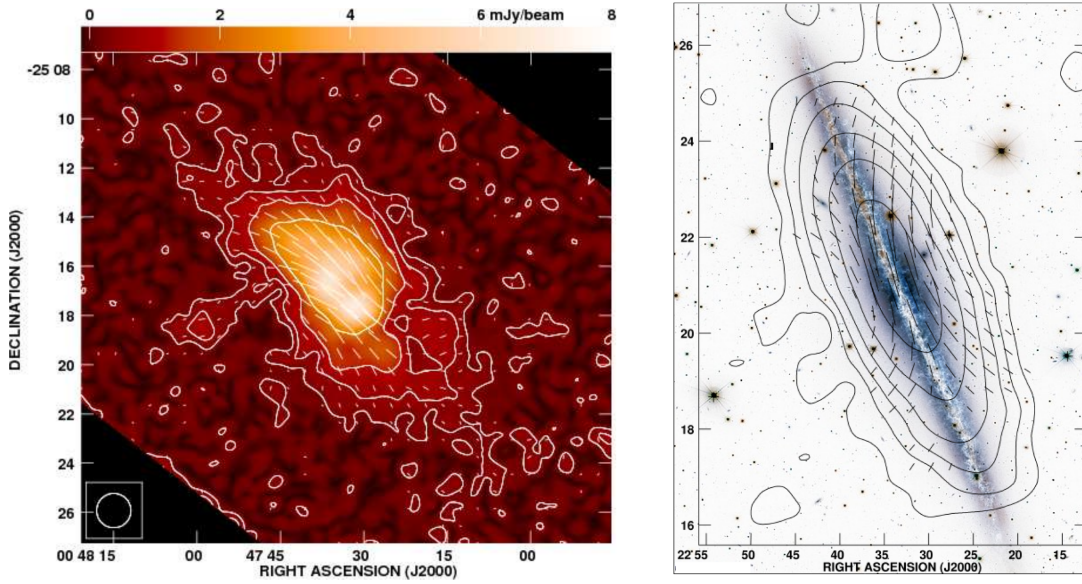


Figure 2.6. X-shaped magnetic-field morphologies in edge-on galaxies. *Left Panel:* NGC 253 [Heesen et al. \(2009\)](#) polarised intensity at $\lambda = 3.6$ cm from Effelsberg observations ($84''$ resolution). Contours at $3, 6, 12,$ and $24 \times 100 \mu\text{Jy beam}^{-1}$ (rms noise level). Vectors show the Faraday-corrected orientation of the large-scale magnetic field; a $1''$ vector corresponds to $50 \mu\text{Jy beam}^{-1}$ of polarised intensity. *Right Panel:* NGC 891 [Krause \(2009\)](#) total radio intensity (contours) and B-vectors at 8.35 GHz ($\lambda = 3.6$ cm), observed with the Effelsberg 100-m telescope.

(iv) *Scaling relations with star formation.* One of the most robust empirical findings is the radio–far-infrared (FIR) correlation, linking synchrotron luminosity to star formation activity (see [Condon, 1992](#) for a review). This relation reflects the common origin in massive stars of the energy source of both FIR and non-thermal synchrotron emission. More detailed studies, both spatially resolved and global, find $B \propto \Sigma_{\text{SFR}}^{0.2-0.4}$, consistent with expectations from small-scale dynamo theory ([Chyży et al., 2011](#); [Schleicher & Beck, 2013](#); [Van Eck et al., 2015](#)) (see Section 1.4). This scaling anchors the theoretical connection between turbulence, star formation, and magnetic amplification.

(v) *Cosmic-ray transport.* Spectral index maps and vertical synchrotron profiles have been used to constrain cosmic-ray propagation mechanisms. In NGC 253, for example, the steepening of radio spectra with height above the disk indicates that CREs are advected by galactic winds rather than transported purely by diffusion ([Heesen et al., 2009](#)). Such analyses link synchrotron observations not only to magnetic fields but also to feedback-driven gas flows.

2.3.2 Limitations

Synchrotron-based estimates of magnetic field strength and structure are powerful, but they rely on assumptions that can break down on sub-kpc scales or in extreme environments (e.g. starburst nuclei). Here we briefly summarise the main caveats and refer to the literature for details.

- Magnetic fields inferred from total intensity usually assume equipartition and a fixed proton–to–electron ratio $k \sim 100$; both can vary with environment, path length, and transport ([Beck & Krause, 2005](#); [Beck, 2015](#)). In compact starbursts, rapid cooling and advection can bias equipartition estimates unless cross-checked with γ -ray or RM constraints ([Yoast-Hull et al., 2013, 2014](#)).
- Free–free emission flattens high-frequency radio spectra and free–free absorption can suppress low-frequency synchrotron. Multi-band decomposition (or ancillary recombination-line data) should be used before deriving B or CRE parameters ([Condon, 1992](#); [Basu et al., 2015](#)).
- Differential Faraday rotation (internal), external RM fluctuations, and unresolved angle structure all depolarise the signal—especially at long wavelengths—reducing both polarisation fraction and polarised intensity ([Burn, 1966](#); [Sokoloff et al., 1998](#); [Beck, 2015](#)). These effects complicate direct comparisons of ordered field strength/morphology across frequencies.

2.4 Thermal dust emission

The thermal emission from interstellar dust provides a complementary tracer of the magnetic field through its polarised component. Modelling the dust continuum emission itself is a necessary first step to interpret both intensity and polarisation. When describing the dust spectral energy distribution (SED), it is commonly assumed that the emission approximates that of a modified blackbody (or greybody), an approach successfully applied for decades to environments ranging from the diffuse interstellar medium to dense star-forming regions and entire galaxies (e.g. [Hensley & Draine, 2021](#)). For a dust surface density Σ_d and frequency-dependent opacity κ_ν , the specific intensity at frequency ν is

$$I_\nu = (1 - e^{-\tau_\nu}) B_\nu(T_d) \simeq \tau_\nu B_\nu(T_d) \quad (\tau_\nu \ll 1), \quad (2.19)$$

with optical depth $\tau_\nu = \kappa_\nu \Sigma_d$ and a modified blackbody opacity

$$\kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0} \right)^\beta, \quad (2.20)$$

where β is the emissivity index ($\beta \sim 1-2$ for typical interstellar dust; [Draine, 2011, 2003](#)). At ALMA Band 6 (211-275 GHz) and 7 (275-373 GHz) the nuclear regions of starbursts can reach moderate optical depths; elsewhere the emission is usually optically thin, so that $I_\nu \propto \kappa_\nu \Sigma_d B_\nu(T_d)$ sets the spectral slope and brightness.

2.4.1 Dust polarisation

Interstellar grains are irregular and aspherical. When their short axes become statistically aligned with the local magnetic field $\mathbf{B}$ (see Figure 2.7 for a schematic representation), thermal emission becomes linearly polarised with E-vectors perpendicular to the POS field; the magnetic field orientation is therefore obtained by rotating polarisation angles by 90° ([Andersson et al., 2015](#)). The leading alignment framework is Radiative Alignment Torque (RAT) theory: an anisotropic radiation field imparts torques that spin up and align sufficiently large grains; collisional damping and randomisation compete with alignment, making the net efficiency dependent on environment properties, such as radiation intensity and anisotropy, gas density/temperature, grain size and composition; ([Hoang & Lazarian, 2008, 2016; Andersson et al., 2015](#)).

A practical expression for the observed (debaised) polarisation fraction is

$$PF_{\text{obs}} \simeq PF_0 R \cos^2 \gamma e^{-2\sigma_\psi^2}, \quad (2.21)$$

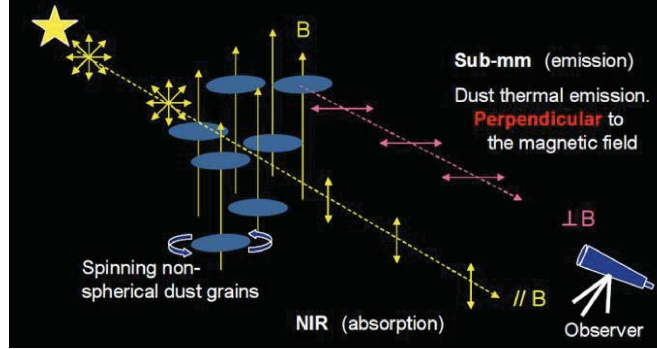


Figure 2.7. Aspherical dust grains spin and align with their minor axes parallel to the magnetic field $\mathbf{B}$. At sub-mm/far-IR wavelengths, thermal emission is polarised with E -vectors perpendicular to $\mathbf{B}$. This 90° difference between emission and absorption is illustrated schematically; the observed polarisation fraction also depends on alignment efficiency, field inclination, and beam/LOS depolarisation. Image from [Su et al., 2013](#).

where PF_0 is the intrinsic polarisation of the grain ensemble, R is the Rayleigh reduction factor (alignment efficiency), γ is the inclination of $\mathbf{B}$ to the POS, and σ_ψ is the dispersion of polarisation angles within the beam/along the line of sight (LOS), which drives beam/LOS depolarisation ([Andersson et al., 2015](#)). Equation (2.21) highlights the main degeneracies: low PF_{obs} may reflect weaker alignment (small R), increased beam/LOS tangling (larger σ_ψ), or a field more inclined to the LOS (larger γ , hence smaller $\cos^2\gamma$). Additional reductions can arise from optical-depth and temperature-mixing effects that are not explicit in Equation (2.21) and are usually absorbed into PF_0 and R .

Polarisation spectrum. The SED of thermal dust emission can be decomposed into its total and polarised components, I_ν , PI_ν . The polarised SED contains information on the composition, size distribution, and alignment efficiency of dust grains, as well as on the local magnetic-field geometry ([Draine & Hensley, 2021](#)).

Figure 2.8 compares the predicted polarisation spectrum with Planck and BLASTPol measurements. Both data and models show that the fractional polarisation is nearly constant between $\sim 100 \mu\text{m}$ and a few millimetres, implying similar emissivity slopes for the total and polarised components in this range. At shorter wavelengths ($< 100 \mu\text{m}$), PF decreases steeply as emission becomes dominated by small, warm, and poorly aligned grains ([Lopez-Rodriguez, 2023](#)). This flat-to-decreasing behaviour of the polarised SED is a key diagnostic of the relative contributions of different grain species and environments, and forms the basis for interpreting multi-band polarimetric observations in both Galactic and extragalactic contexts.

Models of Galactic dust predict distinct behaviours. In starbursts, polarised emission

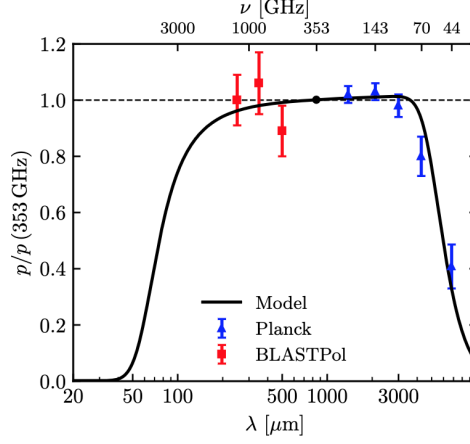


Figure 2.8. Observed and modelled polarised dust spectral energy distribution (SED). Fractional polarisation normalised to its value at 353 GHz, as a function of wavelength. Blue triangles represent Planck measurements, red squares BLASTPol data, and the black line a model from [Draine & Hensley \(2021\)](#) combining aligned silicate grains and unaligned carbonaceous grains. The model reproduces the nearly flat polarisation spectrum observed in the diffuse ISM between 100 μm and 3 mm

from outflows can be warmer (dust temperature $T_d \sim 40\text{--}50\text{ K}$) and shows a steeper effective emissivity index β than disk dust, and the fractional polarisation can vary across 50–850 μm with a minimum commonly within 89–154 μm ([Lopez-Rodriguez 2023, 2022a](#)). By contrast, in optically thin emission and in the Rayleigh limit ($2\pi a \ll \lambda$), $PF(\lambda)$ is frequently close to flat in galactic disks over the far-IR to submm (e.g. [Draine & Hensley, 2021](#)). Outflows and heterogeneous clouds can introduce wavelength-dependent structure in $PF(\lambda)$; multi-band polarimetry is therefore a key discriminant between disk and outflow dust components.

2.4.2 Estimating field strengths from dust polarimetry.

While dust polarisation directly traces the magnetic-field orientation, field strengths must be inferred indirectly by coupling polarisation with gas kinematics. The Davis-Chandrasekhar-Fermi (DCF) method ([Davis & Greenstein, 1951](#); [Chandrasekhar & Fermi, 1953](#)) estimates the plane-of-sky (POS) component under the assumption that small-amplitude, Alfvénic perturbations act on an ordered field $\mathbf{B}$:

$$\delta \mathbf{v}_\perp \simeq \frac{v_A}{B_0} \delta \mathbf{B}_\perp, \quad v_A \equiv \frac{B_0}{\sqrt{4\pi\rho}}, \quad (2.22)$$

where ρ is the gas mass density. For small angular dispersions ($\sigma_\psi \ll 1$), the turbulent-to-ordered POS field ratio satisfies

$$\frac{\langle \delta B_\perp^2 \rangle^{1/2}}{B_0} \approx \sigma_\psi \quad (\text{radians}). \quad (2.23)$$

Combining these relations gives the classical estimator for the POS field strength:

$$B_{\text{POS}} = C \sqrt{4\pi\rho} \frac{\sigma_v}{\sigma_\psi}, \quad (2.24)$$

where σ_v is the non-thermal one-dimensional (line-of-sight) velocity dispersion of the same gas traced by the polarimetry, σ_ψ is the dispersion of polarisation angles after removal of large-scale trends, and $C \sim 0.5\text{--}0.7$ accounts for line-of-sight and beam-integration effects. MHD simulations motivate this range for Q (Ostriker et al., 2001; Heitsch et al., 2001), and analytic/observational angular-dispersion treatments provide consistent corrections (Hildebrand et al., 2009; Houde et al., 2009, 2016).

2.4.3 Systematics and non-magnetic mechanisms.

Interpreting PF and angles requires care:

- *Beam/LOS depolarisation* (field tangling across the beam or along the LOS) suppresses PF and can imprint an anticorrelation between PF and column density N_{H} (Planck Collaboration et al., 2015a, 2016).
- *Optical depth* reduces PF as τ_ν approaches unity and can rotate apparent angles in specific geometries; radiative-transfer effects are strongest in compact nuclear regions (Brauer et al., 2016; Hildebrand et al., 2000). In galactic nuclei, where dust columns are often optically thick, radiative-transfer effects dominate the observed polarisation (Lopez-Rodriguez et al., 2018; Jones et al., 2019; Downes & Eckart, 2007).
- *Self-scattering* of dust thermal emission can polarise continuum emission when the maximum grain size $a_{\text{max}} \sim \lambda/2\pi$ and the radiation field is anisotropic. This mechanism is well established in protoplanetary disks and typically produces characteristic patterns (e.g. alignment with disk minor axis, azimuthal/radial flips) and a strong multi-wavelength signature (Kataoka et al., 2015; Yang et al., 2016). In starburst nuclei, submm self-scattering generally requires very large grains and high optical depths; morphology and the λ -dependence of PF help to rule it in/out.

- *Magnetic dipole emission (MDE)*. Thermal fluctuations of the magnetisation in ferromagnetic/ferrimagnetic nanoparticles (e.g. Fe, Fe₃O₄, γ -Fe₂O₃) embedded in or attached to dust grains produce magnetic-dipole radiation at mm–cm wavelengths. Models predict a spectrum that typically peaks at ~ 10 – 100 GHz and declines toward the submm, so in ALMA Bands 6–7 (211–373 GHz) the contribution is expected to be $\lesssim$ a few per cent for typical ISM conditions—hence subdominant to electric-dipole thermal dust emission (Draine & Hensley, 2013, 2021).

2.5 Dust polarisation observations in galactic and extra galactic environment

Large-scale surveys of polarised dust emission, such as those conducted by Planck, have revealed key trends in galactic environments: PF decreases with increasing column density (N_{H}), indicating stronger depolarisation in regions with disordered magnetic fields. These studies also show that areas with complex magnetic field structures exhibit lower PF , while uniform, large-scale fields maintain higher values. These trends primarily result from geometrical depolarisation, with variations in grain-alignment efficiency due to local radiation and density conditions playing a secondary role (Planck Collaboration et al., 2015a, 2016). Building on these galactic-scale findings, the SALSA survey extends polarisation studies to nearby galaxies.

2.5.1 SALSA survey

The *Survey of extragALactic magnetiSm with SOFIA* (SALSA) represents the first homogeneous FIR polarimetric survey of nearby galaxies. It consists of 14 targets observed with the High-Angular Wideband Camera Plus (HAWC+, Harper et al., 2018; Dowell et al., 2010) across 53 – $214\ \mu\text{m}$ at 5 – 18 arcsec resolution on board of the Stratospheric Observatory For Infrared Astronomy (SOFIA, Ennico et al., 2018; Young et al., 2012; Krabbe, 2000¹).

SALSA established benchmark trends for dust polarisation fractions, spectra, and magnetic morphologies across disks, bars, and outflows (Lopez-Rodriguez et al., 2022a,b). Key results include:

¹SOFIA was a 2.5 m telescope mounted aboard a Boeing 747SP aircraft, operating at altitudes of 12–14 km to access the infrared sky above most of the atmospheric water vapor. Among its suite of instruments, the HAWC+ camera provided imaging polarimetry in five far-infrared (FIR) bands spanning 50 – $240\ \mu\text{m}$, with angular resolutions of ~ 5 – 20 arcsec. Although SOFIA ended operations in 2022, it enabled unique polarimetric capabilities that remain unmatched at these wavelengths.

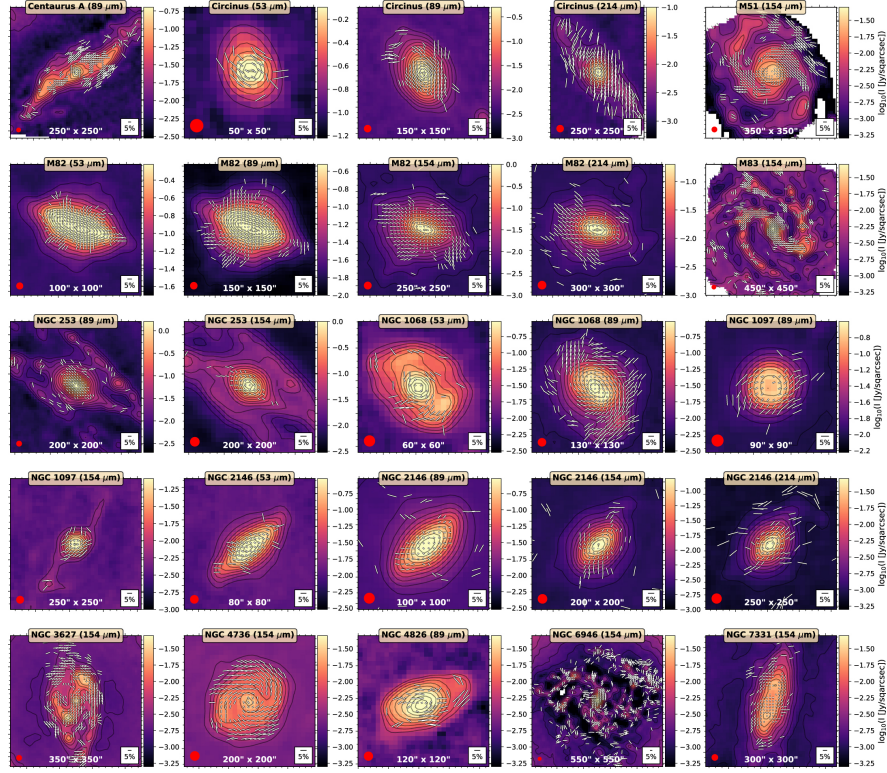


Figure 2.9. Overview of the SALSA galaxy sample. FIR polarisation maps of 14 nearby galaxies observed with SOFIA/HAWC+ at 53–214 μm as part of the *Survey of extragalactic magnetiSm with SOFIA* (SALSA). Contours trace total FIR intensity, while line segments show the plane-of-sky magnetic-field orientation (rotated by 90° from the measured polarisation). Each panel lists the target, observing band, and angular scale; red circles indicate the beam FWHM. The sample spans a range of morphologies—spirals, barred galaxies, starbursts, and AGN hosts—revealing coherent magnetic patterns across disks, bars, and outflows. Image from [Lopez-Rodriguez et al. \(2022a\)](#).

- (i) typical disk-averaged polarisation fractions of $\langle PI_{154\mu\text{m}} \rangle \simeq 3.3 \pm 0.9\%$, with a broad 0–15% range depending on environment;
- (ii) starburst galaxies showing a minimum in the polarisation spectrum between 89–154 μm ;
- (iii) $PF-N_{\text{H}}$ and $PF-T_{\text{d}}$ relations that often require broken power-law fits, consistent with variations in the balance between ordered and random field components and with changes in alignment efficiency ([Lopez-Rodriguez et al., 2022b](#));
- (iv) in resolved galaxies, PF at FIR–mm wavelengths typically ranges from $\sim 0.3\%$ to

a few per cent. Higher values are found in diffuse, ordered inter-arm or outer-disk regions, while compact, high-column-density nuclei show stronger depolarisation from field curvature and sub-beam structure. Large-area SOFIA/HAWC+ maps reveal coherent spiral/bar magnetic patterns and a systematic decline of PF with tracers of dust column and intense radiation fields (Lopez-Rodriguez et al., 2022a). In M 51, strong radiation fields can drive radiative torque disruption (RAT-D), fragmenting large grains and shifting the aligned population to smaller sizes, thereby reducing PF where the radiation is most intense (Lopez-Rodriguez & Tram, 2024).

A companion SALSA study comparing FIR (HAWC+) and radio (3–6 cm) polarimetry finds that FIR polarisation more cleanly traces magnetic fields in outflows, while radio polarisation preferentially traces more diffuse, warm phases; FIR magnetic fields are typically 2–75% more turbulent than radio magnetic fields in spirals (Borlaff et al., 2023). The SALSA program has also explored the physical interpretation of FIR/radio geometries using MHD simulations (tomographic comparison) (Martin-Alvarez et al., 2023) and presented case studies such as the barred galaxy NGC 1097, where FIR polarisation reveals magnetically-guided gas flows feeding the starburst ring and nucleus (Lopez-Rodriguez et al., 2021). For NGC 253 specifically, early HAWC+ observations at $89\,\mu\text{m}$ already indicated a largely planar field in the tilted disk with weak vertical components near the minor axis (Jones et al., 2019), consistent with the SALSA view that FIR polarimetry is particularly sensitive to dusty outflows in starbursts.

2.5.2 ALMA dust polarisation observations

The low resolution of SOFIA’s observations does not resolve the turbulent coherence length of the magnetic field in galaxies, preventing the actual quantification of magnetic field energy. In recent years, the Atacama Large Millimeter/Submillimeter Array (ALMA) has started providing polarimetric observations at (sub)millimetre wavelengths (see A2 for some technical details) with sub-arcsecond resolution. At these resolutions corresponding for nearby galaxies to tens of parsecs, the coherence scale of magnetic field can be resolved, and measurements are less affected by depolarization effects.

The current sample of ALMA dust polarisation observations of nearby galaxies is very limited, and concentrate actually on bright, nearby, and extreme systems. The first detection of dust polarized emission on a nearby galaxy was reported by (Lopez-Rodriguez et al., 2020), observing the dusty torus of NGC 1068. The polarized torus has an asymmetric variation across the equatorial axis arising from an inhomogeneous optical depth, and a variation of the magnetic field turbulence at sub-pc scales. The

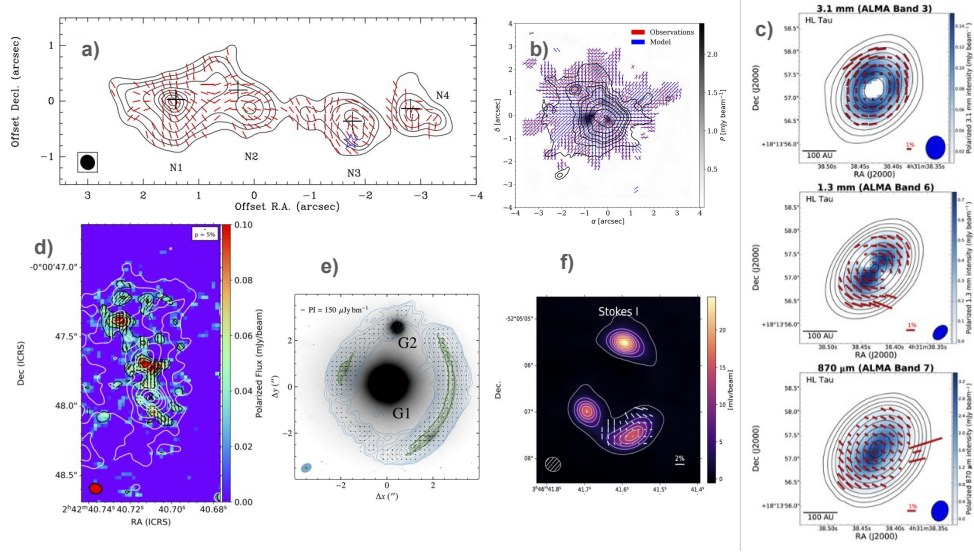


Figure 2.10. A selection of ALMA dust-polarization observations of Galactic (panels a–c) and extragalactic (panels d–f) targets. (a) *W51 North*: a luminous high-mass protostar. ALMA Band 6 at 230 GHz with 0.0026 arcsec resolution, resolving individual cores. Magnetic-field orientations are shown as red segments; black contours show Stokes I . The blue star marks ultra-compact H II regions. Image from Koch et al. (2018). (b) *G31.41+0.31*: a hot molecular core. Polarization angles showing the magnetic-field direction from observations (red) and the best model (blue). The gray-scale map shows polarized intensity P ; black contours show the 1.3 mm dust emission. Image from Beltrán et al. (2019). (c) *HL Tau*: a protostellar disk. ALMA polarimetric observations at 3.1 mm (top), 1.3 mm (middle), and 870 μm (bottom). Red vectors show the $> 3\sigma$ polarization morphology, with lengths $\propto P$. The color scale shows polarized intensity. These data reveal a wavelength-dependent transition in (sub)millimeter polarization morphology not consistent with grains aligned with a purely toroidal magnetic field. Figure from Stephens et al. (2017). (d) *NGC 1068*: a nearby AGN. Polarized flux (color scale) with overlaid polarization E -vectors (black) in the central region; total flux is shown with white contours. The image shows asymmetric polarization across the equatorial axis of the torus. Image from Lopez-Rodriguez et al. (2020). (e) *HERS J020941.1+001557*: a gravitationally lensed dusty star-forming galaxy at $z = 2.55$. Polarization angles (black segments) measured with ALMA Band 7. Blue and green contours show naturally weighted emission in compact and extended configurations, respectively. Figure from de Roo et al. (2025). (f) *SPT0346-52*: a strongly lensed dusty star-forming galaxy at $z = 5.6$. Stokes I image (color map and contours). Light-blue vectors show magnetic-field orientation, with length proportional to the polarized fraction. Image from Chen et al. (2024).

observations and modeling constrain the torus properties strongly supporting that magnetic fields up to a few pc contribute to the accretion flow onto the active nuclei. The observations of NGC 253, described in this thesis (see Chapter 3) provide the first detection of dust polarization in a starburst galaxy.

Additionally, ALMA has detected linearly polarised thermal emission in strongly lensed dusty star-forming galaxies at high redshift, opening new avenues for studying magnetization in the early Universe ([Chen et al., 2024](#); [de Roo et al., 2025](#)).

In the Milky Way, ALMA routinely observes star-forming regions, revealing ordered magnetic fields on cores and envelope scales. To mention just a few of the first results obtained with ALMA, [Koch et al. \(2018\)](#) studied the high-mass star-forming region W51, identifying cometary-shaped magnetic field morphologies in satellite cores and streamlined structures. Similarly, [Beltrán et al. \(2019\)](#) observed an hourglass-shaped magnetic field in G31.41+0.31, one of the clearest examples in a high-mass star-forming region. Using the Fermi-Chandrasekhar method, they found the field to be dynamically significant but insufficient to prevent core fragmentation and collapse.

ALMA has also clarified the nature of polarised submillimeter emission in protostellar disks, where self-scattering by grains comparable in size to the wavelength, rather than magnetic field alignment, often dominates polarisation ([Stephens et al., 2017](#)) (see Section 2.4.3).

Fig. 2.10 presents a collection of representative figures taken from these publications.

Appendix A2: ALMA full polarisation capabilities

ALMA is an interferometer of 66 high-precision antennas located on the Chajnantor plain of the Chilean Andes. Fifty of these antennas are 12-meter antennas, used for sensitive, high-resolution imaging. This 12-m array is complemented by the Atacama Compact Array (ACA - Morita Array) , composed of 12 closely spaced 7-m antennas, and four 12-m antennas for single-dish observations, to recover the emission at the most extended spatial scales.

ALMA antennas are provided with linear feed which split the incoming signal into two linear orthogonal polarisations (X and Y). The Correlator then produces correlation pairs of $\langle XX^* \rangle$, $\langle XY^* \rangle$, $\langle YX^* \rangle$, and $\langle YY^* \rangle$. These correlations relate to the Stokes visibilities of I, Q, U, and V. Ideally the relation between the observed cross-correlated visibilities V_{pq} where p and q represent the polarisation output X and Y, would be

$$I = \frac{V_{XX} + V_{YY}}{2}, \quad Q = \frac{V_{XX} - V_{YY}}{2}, \quad U = \frac{V_{XY} + V_{YX}}{2}, \quad V = \frac{V_{XY} - V_{YX}}{2i} \quad (2.25)$$

In reality, there are many terms corrupting the visibilities which prevent the use of this simple and direct equations (see [Sault et al., 1996](#) and [Hales, 2017](#), for a formal description), and need to be calibrated.

Given the imperfections in the feed construction, during the splitting of the incoming radiation into two orthogonal components small projections of one component can "leak" into the other, producing an instrumental polarisation (D-terms) or leakages. Assuming that any order terms involving instrumental polarisation > 1 can be ignored the linearized approximation for the visibilities in eq. 2.25 is:

$$V_{XX} = (\mathcal{I} + Q_\psi) + \mathcal{U}_\psi(d_{xj}^* + d_{xi}) + i\mathcal{V}(d_{xj}^* + d_{xi}) \quad (2.26)$$

$$V_{XY} = (\mathcal{U}_\psi + i\mathcal{V}) + \mathcal{I}(d_{yj}^* + d_{xi}) + Q_\psi(d_{yj}^* + d_{xi}) \quad (2.27)$$

$$V_{YX} = (\mathcal{U}_\psi - i\mathcal{V}) + \mathcal{I}(d_{yi} + d_{xj}^*) + Q_\psi(d_{yi} - d_{xi}^*) \quad (2.28)$$

$$V_{YY} = (\mathcal{I} - Q_\psi) + \mathcal{U}_\psi(d_{yi} + d_{yj}^*) + i\mathcal{V}(d_{yi} - d_{yj}^*) \quad (2.29)$$

where d_{pj} are the D-terms as a function of polarisation and antenna, the asterisk denotes complex conjugates, and $\mathcal{U}_\psi$ and Q_ψ are the Stokes parameters as a function of the parallactic angle (so changing in time).

From these equations it is clear that in all correlations there is a source linear polarisation term (Q_ψ and U_ψ) which varies with time, scaled by D-terms (eq. 2.26 -

2.29), while in the cross-hands (eq. 2.27, 2.28) there is a complex offset proportional to I , constant in time.

The most straightforward way to calibrate the D-terms would be to observe an unpolarised source, where the cross-hands output would be purely D-terms since Stokes Q, U, and V would have no signal. However, bright and unpolarised astronomical sources are rarely found, in particular at mm wavelengths. Therefore, ALMA uses quasars (with linear polarisation higher than 2%) as polarisation calibrators. Their observation over a wide enough range ($> 60^\circ$) of parallactic angle allows to actually solve these equations to derive the intrinsic polarisation of the source and the instrumental polarisation. This is indeed the actual strategy used for the standard calibration of ALMA full polarisation data, described in (Nagai et al., 2016) and in the casaguide².

Some other additional terms are corrupting the visibilities:

- The signal path followed by each of the individual polarisations is slightly different, introducing a small delay in the signal that needs to be accounted for.
- The use of a reference antenna in the usual total intensity calibration, arbitrarily sets both X and Y phases of an antenna to zero. This results in the inverse of its X-Y offset being transferred on the cross-hand phases of the other antennas, which need to be calibrated.
- An additional instrumental effect is due to receiver feeds offset with respect to the axis of the reflector. This introduces off-axis errors in both linear and circular polarisation.

This last off-axis instrumental polarisation is currently not calibrated, this results in the limitation of ALMA nominal calibration accuracy to the inner 1/3 of the primary beam FWHM for linear polarisation and to the inner 1/10 for circular.

Inside these regions, the expected minimum detectable degree of linear polarisation, defined as three times the systematic calibration uncertainty, is 0.1% for linear polarisation and 1.8% of the peak flux for circular polarisation. The accuracy of absolute polarisation position angle in a single-pointing image is 1° within the inner 1/3 of the FWHM of the primary beam, increasing to as much as 5° near the FWHM. These levels of accuracy will only be reached if there is sufficient signal-to-noise in the polarised emission (see ALMA technical handbook³).

²https://casaguides.nrao.edu/index.php?title=3C286_polarisation

³<https://almascience.eso.org/documents-and-tools/cycle12/alma-technical-handbook>

3

Observations of NGC 253 with ALMA

This chapter presents the ALMA full-Stokes observations of the nearby starburst galaxy NGC 253, the closest example of an intense nuclear starburst driving a multiphase galactic wind. The aim is to characterise the magnetic-field morphology and its connection with star formation and outflows through high-resolution polarimetric data at (sub)millimetre wavelengths.

We begin in Section 3.1 by introducing the target galaxy, summarising its physical properties, starburst activity, and multiphase outflow, and highlighting why NGC 253 is an ideal laboratory for studying magnetic fields in extreme environments. Section 3.2 describes the ALMA Band 4 (145 GHz) and Band 7 (345 GHz) observations, including their setup and calibration strategy, while Section 3.3 outlines the full-Stokes calibration, imaging procedures, and resulting image characteristics.

Section 3.4 presents our treatment of noise and uncertainty propagation, including the computation of the full covariance matrix for the Stokes parameters, which is later used to debias the polarisation measurements. Section 3.5 summarises the complementary archival data from ALMA and the VLA employed in the spectral-energy-distribution (SED) analysis.

Section 3.6 introduces the resulting polarisation and magnetic-field maps, quantifying the spatial distribution of polarised intensity, polarisation fraction, and magnetic-field orientation at both ALMA bands. In Section 3.7 we disentangle the relative contributions of synchrotron, free-free, and dust emission through SED fitting and derive the intrinsic polarisation fractions of each component.

Section 3.8 examines the link between the magnetic-field morphology, the super star clusters (SSCs), and the large-scale outflow, using multi-wavelength comparisons to trace how the field couples to the galactic wind. The correlation between the polarisation fraction and gas column density, as well as between the polarisation fraction and the polarisation-angle dispersion function, are discussed in Section 3.8.2 and Section 3.8.3, respectively, to connect our measurements with previous Galactic trends.

Chapter 3.9 presents a summary of the main results, emphasising the physical interpretation of the observed polarisation structure and its implications for the interplay

between magnetic fields, star formation, and feedback in NGC 253.

Appendix A3 presents a detailed validation of the polarisation calibration in both the image and visibility domains, while Appendix B3 evaluates the robustness of the polarisation angle dispersion function with respect to the adopted scale.

3.1 The starburst galaxy NGC 253

NGC 253 is a nearby, highly inclined, tilted, starburst galaxy (distance $D = 3.5$ Mpc, inclination $i \sim 78^\circ$, position angle of the long axis $\theta \sim 52^\circ$; [Rekola et al., 2005](#); [Pence, 1980](#); [Lucero et al., 2015](#)). As the nearest system hosting an exceptional multiphase galactic wind, it has been extensively studied in many wavebands, including X-ray ([Strickland et al., 2000](#)), optical ([Watson et al., 1996](#)), infrared ([Sugai et al., 2003](#)), sub-millimetre ([Bolatto et al., 2013b](#)), and GHz radio, including polarisation ([Turner & Ho, 1985](#); [Heesen et al., 2009, 2011](#)). The central starburst activity in NGC 253 is fuelled by gas accretion along the bar ([Paglione et al., 2004](#)), resulting in a SFR of $\approx 2 M_\odot \text{ yr}^{-1}$ ([Bendo et al., 2015](#); [Leroy et al., 2015](#); [Ott et al., 2005](#)) across the central ~ 300 parsecs. This nuclear region, which is the focus of the ALMA observations discussed in this chapter, is indicated by a white dashed circle in its larger galactic context in Figure 3.1. The intense star formation in this area drives a massive multiphase outflow ([Walter et al., 2017](#)), whose hot component is prominently traced by X-ray emission emerging perpendicular to the disk ([Lopez et al., 2023](#)) (shown in Figure 3.1). In this region, signatures of shock activity have also been detected ([Humire et al., 2025](#)). The mass outflow rate has been estimated to be $14 - 39 M_\odot \text{ yr}^{-1}$ in the cool molecular phase ([Krieger et al., 2019](#)) and approximately $2.8 M_\odot \text{ yr}^{-1}$ for the north-western side and around $3.2 M_\odot \text{ yr}^{-1}$ for the south-eastern side in the warm ionised phase ([Lopez et al., 2023](#)). Recently, the molecular gas content of NGC 253’s outflow and the nascent superstar clusters (SSCs) that account for a large fraction of the star formation activity in the nuclear starburst have been studied in detail with ALMA (e.g. [Bolatto et al., 2013b](#); [Leroy et al., 2015](#); [Zschaechner et al., 2018](#); [Leroy et al., 2018](#); [Krieger et al., 2019](#); [Levy et al., 2021](#); [Mills et al., 2021](#); [Levy et al., 2022](#)). These studies have shown that the outflowing molecular gas is located mostly around the edge of the wind. The most prominent outflow structure in ALMA molecular emission line maps is the south-western streamer, from which ~ 350 GHz dust continuum emission has also been detected. Estimates of the molecular mass outflow rate range between $\sim 3 - 9 M_\odot \text{ yr}^{-1}$ ([Bolatto et al., 2013b](#)) and $\sim 25 - 50 M_\odot \text{ yr}^{-1}$ ([Zschaechner et al., 2018](#)), that is, a mass-loading factor of ~ 5 . The SSCs in the centre of NGC 253 are

young $\sim 0.01 - 3$ Myr, with typical stellar masses of $10^4 - 10^6 M_{\odot}$ and a full width at half maximum (FWHM) sizes of $0.4 - 0.7$ pc. As projected on the sky, the SSCs appear to be aligned along a thin linear structure with length ~ 150 pc. Modelling of the SSCs' morphology and kinematics suggests that they are distributed on an elliptical ring with a semimajor (semiminor) axis of 110 (60) pc, which we observe edge-on (Levy et al., 2022).

At far-infrared to radio wavelengths, NGC 253's integrated SED is well-described by a combination of synchrotron, free-free and thermal dust emission, with a very steep synchrotron spectrum at high radio frequencies (Peel et al., 2011). Thermal dust emission seems to dominate the global SED at the frequencies of ALMA Band 4 (145 GHz) and Band 7 (343.5 GHz). As one of the nearest galaxies with an extremely bright dust continuum (7.4 Jy at 353 GHz, Planck Collaboration et al., 2011), NGC 253 is an ideal target for extragalactic dust polarisation studies. SOFIA/HAWC+ observations by SALSA at 89 and $154 \mu\text{m}$ indicate that on ~ 100 pc spatial scales, the thermal dust emission is $\sim 1\%$ polarised in the central region, with higher polarisation fractions further out in the disk. The orientation of the magnetic field inferred from the SALSA measurements suggests that the magnetic field traced by dust (Lopez-Rodriguez & Tram, 2024) is preferentially aligned with the galactic disk, except in the central region where the field also shows perpendicular structure (Lopez-Rodriguez, 2023; Lopez-Rodriguez et al., 2022a).

3.2 ALMA observations

The ALMA observations were designed to characterise the magnetic-field structure in the central starburst region of NGC 253, focusing on the disk–halo interface at the base of the starburst-driven outflow within the central ~ 300 pc. This region is critical for assessing how the orientation and degree of magnetic-field ordering may influence the entrainment and survival of cold gas in the wind.

To address these goals, full-Stokes continuum observations were obtained in Band 7 (Mahieu et al., 2012) and Band 4 (Asayama et al., 2014) (see Appendix A2 for technical details), providing complementary sensitivity to magnetic fields traced by dust emission on $\sim 5\text{--}50$ pc scales and to the larger-scale field geometry on $\sim 40\text{--}300$ pc scales, respectively. Band 7 observations were designed to resolve the magnetic field in dense star-forming gas and molecular cloud structures in the nuclear starburst, while Band 4 observations target the larger-scale magnetic field geometry across the disk–halo interface, overlapping the spatial scales probed by existing radio polarisation studies.

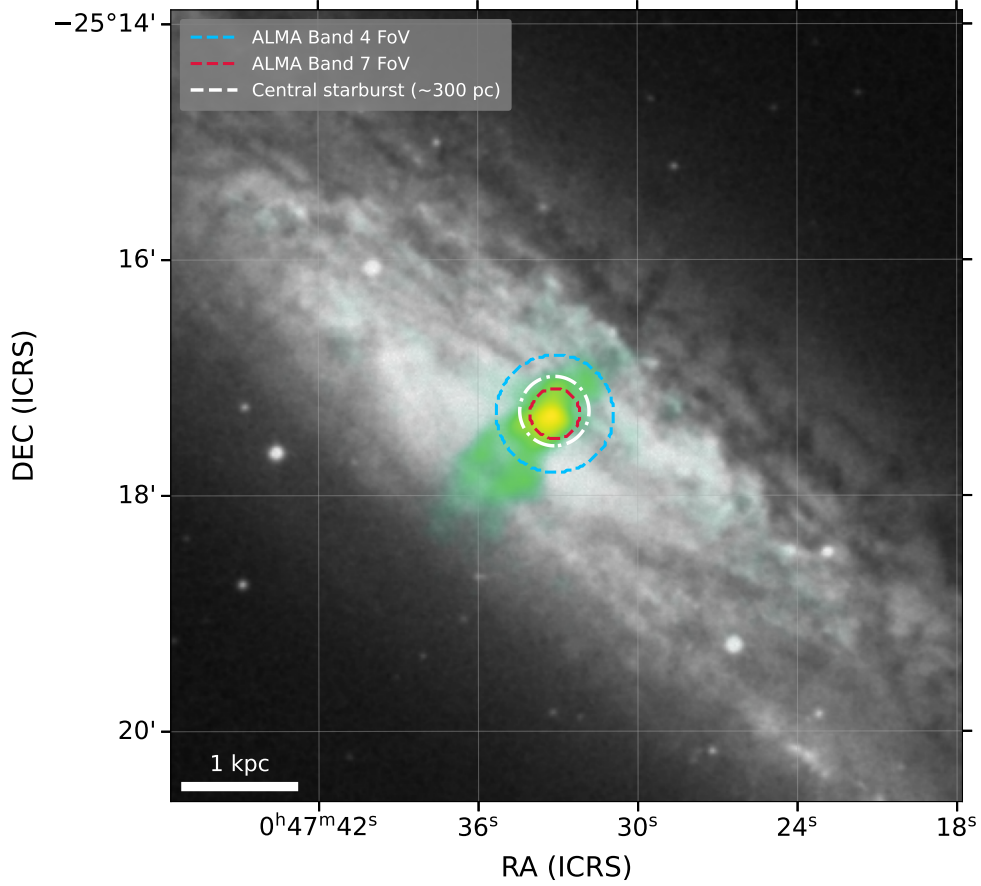


Figure 3.1. Optical/near-infrared Digitized Sky Survey (DSS2) image of NGC 253, obtained from the Second Epoch Survey with the UK Schmidt Telescope (SERC-IR photographic band, $\lambda \sim 0.8\text{--}0.9\,\mu\text{m}$; observed in 1980), showing the large-scale morphology of the galaxy and the location of the ALMA observations analysed in this chapter. Blue and red dashed contours indicate the field of views of the ALMA Band 4 (145 GHz) and Band 7 (345 GHz) observations, respectively. The fields of view are centred on the nuclear starburst region (highlighted with white dashed contours) and encompass the base of the multiphase outflow, whose hot component is traced by X-ray emission (Lopez et al., 2023), which is the focus of the polarimetric analysis presented in this work.

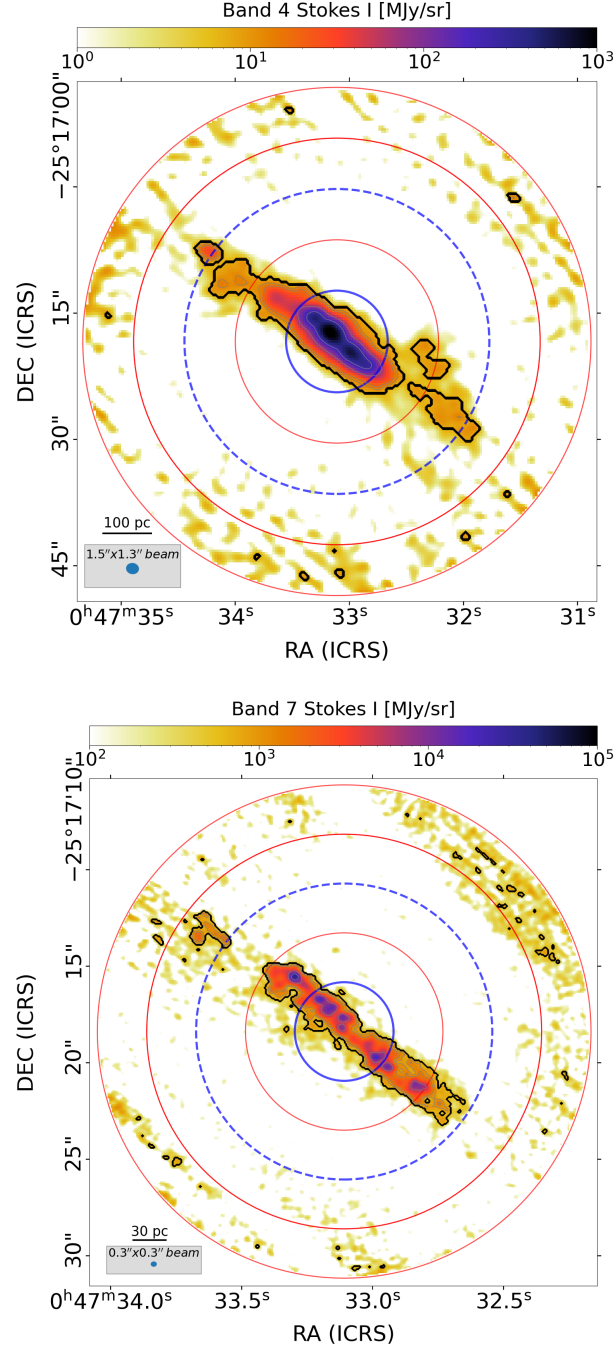


Figure 3.2. Total intensity images. Band 4 (~ 145 GHz) is shown on the top panel, Band 7 (~ 345 GHz) on the bottom panel. The thick black contour corresponds to $3 \times \sigma_I$, while the grey thin contours correspond to $[5, 7, 10, 30, 100] \times \sigma_I$. The concentric circles overlaid on the images are the annular regions used for the noise analysis (see Section 3.4). The thick and dotted blue circles correspond to $1/3$ of the HPBW and the full HPBW of the image, respectively. The red circles have as radii multiples of $n \times 1/3$ of the HPBW, where n ranges from 2 to 5.

Band	ν_{LO} (GHz)	ν_{spw} (GHz)				Date	PAR span (deg)	PF (%)	PA (deg)
		spw1	spw2	spw3	spw4				
4	145	137.99	139.93	149.99	151.99	22.01.2019	70	3.78	18
		137.99	139.93	149.99	151.99	17.11.2019	120	3.95	71.6
7	343.5	336.49	338.43	348.49	350.49	28.04.2019	100	2.73	36.9
		336.49	338.43	348.49	350.49	30.04.2019	100	2.93	36.5

Table 3.1. Column 2 lists the Local Oscillator frequency (ν_{LO}). Columns 3–6 list the central frequencies of the four spectral windows (ν_{spw}) as reported by the CASA `listobs` task. Column 8 gives the parallactic-angle coverage achieved during each session. Columns 9 and 10 report the polarisation fraction (PF) and angle (PA) of the calibrator J0006–0623; values agree with monitoring results.

This dual-band approach enables a direct comparison of magnetic field properties across spatial scales and emission regimes.

The observations consisted of single-pointing mosaics centred on the nuclear starburst region, with primary-beam FWHM of $\sim 18''$ (Band 7) and $\sim 42''$ (Band 4). The corresponding fields of view are shown in Fig. 3.1 as red and blue dashed contours, respectively, while the total intensity maps are presented in Fig. 3.2.

Full polarisation data were acquired using the standard continuum polarisation setup in time-division mode (TDM), recording the four cross-correlation products (XX, XY, YX, YY) across four 2 GHz spectral windows, each divided into 64 channels. The central frequencies of the two bands are listed in Table 3.1. Observations were carried out using the C43-4 configuration in Band 7 and the more compact C43-1 configuration in Band 4, yielding nominal angular resolutions of $0.3''$ and $1.7''$, and maximum recoverable scales of $\sim 3.8''$ and $\sim 15''$, respectively.

The observations followed the standard session-based observing scheme adopted for ALMA polarisation projects, in which the same schedule is executed repeatedly until sufficient parallactic-angle coverage is achieved for accurate instrumental polarisation calibration. A minimum coverage of $\sim 60^\circ$ is required and is typically reached with two to three executions. Table 3.1 summarises the individual sessions and the corresponding properties of the polarisation calibrator J0006–0623, which was used for both bands and observed regularly within the phase-calibrator–science-target loop.

The quasar J0038–2459 served as the phase calibrator for both bands, while flux density and bandpass calibration were performed using J0006–0623. In Band 7, observations of the additional quasar J0046–2691 were included as an independent check of the calibration solutions.

3.3 Calibration

The data were calibrated using the CASA software package (version 5.6.1, [CASA Team et al., 2022](#)) and the standard calibration scripts provided by the observatory. The current calibration scheme for polarisation projects is summarised in [Nagai et al. \(2016\)](#) and in the ALMA polarisation casaguide¹. A concise overview of ALMA’s full-polarisation capabilities and calibration procedure is provided in Appendix A2.

The total intensity calibration, deriving frequency and time dependent gains, is performed for each observing execution, while the polarisation calibration is done per session (combining consecutive executions). This calibration assumes that the polarisation calibrator has no circular polarisation (Stokes $V = 0$) and it derives the linear polarisation properties of the calibrator as well as the instrumental polarisation from the data, exploiting the parallactic angle variation. Table 3.1 reports the calibrator’s linear polarisation ratio, polarisation angle and parallactic angle range determined from the different sessions. We observed a 90° wrap of the parallactic angle range in our Band 4 observations. This is due to an intrinsic variation of the calibrator’s properties at all frequencies, as reported in the monitoring survey².

The instrumental polarisation gains that we derived ($D_{\text{terms}} < 4\%$ for each antenna) were applied to all sources. To confirm the quality of the calibration, an image of the polarisation calibrator for each session was made. The Stokes I flux is normalised by the calibration procedure, so we measure a peak of ~ 1 Jy/beam in both bands. The Stokes V images show no signs of residual instrumental polarisation. They have a root mean square (RMS) of 0.015 mJy/beam and 0.030 mJy/beam in Band 4 and Band 7, respectively.

Additional validation of the polarisation calibration was performed by inspecting the cross-hand visibilities (XY and YX) of the polarisation calibrator in the visibility domain and by imaging the calibrators in full Stokes after the application of the complete calibration. In particular, we examined the distribution of the XY and YX visibilities in the complex plane both before and after calibration, and inspected their amplitude and phase as a function of frequency for a set of representative baselines. In addition, images of the calibrator were produced in Stokes I, Q, U, and V in order to verify the absence of residual instrumental or calibration-induced structures. The corresponding diagnostic plots are presented in Appendix A3.

¹https://casaguides.nrao.edu/index.php?title=3C286_polarisation

²<http://www.alma.cl/~skameno/AMAPOLA>

Band	bmaj ["]	bmin ["]	bpa [deg]	σ_I	σ_Q [MJy/sr]	σ_U
4	1.54	1.33	81.2	2.98	0.37	0.36
	2.2	2.2	0	2.51	0.15	0.15
7	0.32	0.28	-88.5	227.67	23.24	24.34
	1.54	1.33	81.2	149.05	3.18	4.80
	2.2	2.2	0	121.67	2.16	3.38

Table 3.2. RMS of the Band 4 and Band 7 Stokes I, Q and U images measured at the different resolutions used in this analysis. For each band, the properties of the images at the native resolution are reported in the first row.

3.3.1 Full-Stokes imaging

The calibrated sessions for each band were combined and imaged using the CASA task *tclean*. Continuum full Stokes (I, Q, U, V) images of the target and the calibrators were obtained in multi-frequency mode (mfs), using the *clarkstokes* deconvolver algorithm in which a Clark clean operates separately on each Stokes plane. A Briggs weighting scheme (Briggs, 1995) with robust = 0.2 and 0.5 was used for imaging of Band 4 and 7 respectively. The resulting images in Band 4 have a synthesised beam of $1.54 \times 1.33''$ (26.1×22.1 pc), with a beam position angle bpa=81.2 deg, and in Band 7 a beam of $0.32 \times 0.28''$ (5.4×4.8 pc), with a bpa=-88.5 deg. The RMS measured in Stokes I, Q and U, are reported in Table 3.2; these values are consistent with expectations from the radiometer formula. Stokes I images, shown in Figure 3.2, are dynamic range limited in both Bands 4 and 7 with a signal-to-noise ratio (S/N) of 500 and 180, respectively.

In order to compare the results at the two different frequencies, we convolved the data to a common resolution of $1.54 \times 1.33''$ (i.e. the Band 4 resolution). Additionally, the spectral energy distribution analysis presented in Section 3.7 required us to homogenise the data at all frequencies to the resolution of the archival VLA L-band data ($2.2 \times 2.2''$, ~ 37 pc). Table 3.2 reports the noise characteristics of the images at the different resolutions that we use in our analysis.

3.4 Noise analysis

From the Stokes Q and U images, we constructed images of the linearly polarised intensity $PI = \sqrt{Q^2 + U^2}$, the polarisation fraction $PF = PI/I$, and the polarisation angle $PA = 1/2 \arctan(U/Q)$. In polarisation studies, strong assumptions are often made about the noise properties of the measurements, such as neglecting the correlation

between the total and polarised intensities and between the noise in Stokes Q and U images. Nevertheless, the covariance between the Stokes parameters can have a complex effect on the non-linear quantities derived, such as PF, PI, and PA, especially at low S/N (e.g., [Montier et al., 2015a](#)). For this reason, we decided to compute the uncertainties taking into account the full covariance matrix of the Stokes I, Q, and U components. This is defined as

$$\Sigma = \begin{bmatrix} \sigma_{II} & \sigma_{IQ} & \sigma_{IU} \\ \sigma_{IQ} & \sigma_{QQ} & \sigma_{QU} \\ \sigma_{IU} & \sigma_{QU} & \sigma_{UU} \end{bmatrix}, \quad (3.1)$$

where σ_{XY} is the covariance between the variables X and Y.

In real polarisation observations, including interferometric data such as those from ALMA, the off-diagonal covariance components (σ_{IQ} , σ_{IU} , σ_{QU}) are typically non-zero. These correlations arise from instrumental effects, residual atmospheric systematics, and map-making processes (e.g., deconvolution and primary beam correction), which couple noise across the Stokes parameters ([Montier et al., 2015a](#); [Planck Collaboration et al., 2015a](#)). Even after careful calibration, small but non-negligible off-diagonal terms often remain and can affect the bias and uncertainty of the derived polarisation quantities if neglected.

We assume that circular polarisation (i.e. Stokes V) can be neglected. We compute the uncertainties on PF , PI , and PA taking into account the full covariance matrix. In this case, the noise in our derived quantities may be defined as follows:

$$\sigma_{PF}^2 = \frac{1}{PF^2 I^4} (Q^2 \sigma_{QQ} + U^2 \sigma_{UU} + PF^4 I^2 \sigma_{II} + 2QU \sigma_{QU} - 2IQPF^2 \sigma_{IQ} - 2IUPF^2 \sigma_{IU}) \quad (3.2)$$

$$\sigma_{PI}^2 = \frac{1}{PI^2} (Q^2 \sigma_{QQ} + U^2 \sigma_{UU} + 2QU \sigma_{QU}) \quad [(MJy/sr)^2] \quad (3.3)$$

$$\sigma_{PA}^2 = \frac{1}{4} \frac{Q^2 \sigma_{UU} + U^2 \sigma_{QQ} - 2QU \sigma_{QU}}{(Q^2 + U^2)^2} \quad [rad^2]. \quad (3.4)$$

Readers can refer to [Montier et al. \(2015a\)](#) and appendix B1 of [Planck Collaboration et al. \(2015a\)](#) for a full discussion on the impact of noise on estimates of PF , PI , and PA . Since the ALMA data are provided with no per-pixel estimate of the noise correlation matrix, we estimate the noise correlation matrix elements of Equation 3.1 by computing covariances in signal-free regions of the I, Q, and U maps. We divided the images into five annuli of increasing radius (see Figure 3.2). The central region is a circle with a radius equal to one-third of the Half Power Beam Width (HPBW) of

Ring	σ_{II}	σ_{IQ}	σ_{IU}	σ_{QQ}	σ_{UU}	σ_{QU}
Band 4 [(MJy/sr) ²]						
0 (inner 1/3)	6.70	-0.06	-0.03	0.04	0.04	6.9E-03
1	7.55	0.09	-0.13	0.03	0.03	-3.0E-03
2	6.66	0.03	-0.04	0.04	0.04	2.1E-03
3	4.80	4.14E-03	0.02	0.08	0.08	2.5E-03
4	10.31	0.03	-0.08	0.21	0.20	9.6E-03
Band 7 [(MJy/sr) ²]						
0 (inner 1/3)	3.96E+04	-257.28	-14.19	98.58	106.45	15.46
1	3.24E+04	56.80	-28.09	105.77	130.86	-1.82
2	2.79E+04	121.77	50.77	168.56	202.37	7.78
3	3.42E+04	-9.98	-24.79	351.89	408.84	0.13
4	7.13E+04	4.54	-156.03	833.56	939.74	4.57

Table 3.3. Elements of the noise covariance matrix. These values were computed at native resolution as measured in the ALMA maps of NGC 253. Each row corresponds to a different ring shown on Figure 3.2.

the antenna primary beam. The subsequent concentric rings are determined by circles with radii $r_i = n \times 1/3 \times \text{HPBW}$, with n ranging from 2 to 5. In each region, we computed the covariance matrix excluding the pixels with total intensity greater than 0.16 mJy/beam and 0.47 mJy/beam, corresponding to three times the RMS of the total intensity Band 4 and 7 images, respectively. The covariance matrix elements thus computed for each ring are listed in Table 3.3. The derived values are then employed to estimate the uncertainties in PF , PI , and PA for all pixels of that ring. These values are also used to debias the measured PF , following the modified asymptotic estimator formula proposed in [Plaszczynski et al. \(2014\)](#). The variances of the covariance matrix elements σ_{QQ} and σ_{UU} are roughly constant in the first three rings, as it is shown on Table 3.3. This would suggest the absence of large systematics outside the 1/3 of the HPBW. In order to facilitate a more direct comparison of the data in the two Bands, we converted the PI and total intensity estimates and relative uncertainties to MJy/sr. The scale factors of the conversion from Jy/beam to MJy/sr are 18310 and 431673 for Band 4 and 7, respectively.

3.5 Ancillary data

For the SED analysis presented in Section 3.7, we assembled archival data covering the frequency range from 1.4 GHz ($\lambda \sim 20$ cm) to 350 GHz ($\lambda \sim 0.9$ mm) taken with ALMA and the Very Large Array (VLA). The high frequency data are taken from the ALMA archive, and have resolutions ranging from ~ 1 to $1.7''$. The low frequency data are taken from VLA archive, and the image at the lowest frequency (1.4 GHz) has a

resolution of $2.2''$. The data at all frequencies were convolved to this resolution for the SED analysis. The original resolution of each image is reported in Table 3.5, as well as the largest angular scale recovered, and the corresponding project code.

The images at 22 and 33 GHz used in the SED analysis in Section 3.7 were presented by [Gorski et al. \(2017, 2019\)](#), and were obtained as part of the VLA project 16B-337. The resolutions of these datasets are $0.204'' \times 0.121''$ and $0.096'' \times 0.045''$, with maximum recoverable scales of $2.4''$ and $1.6''$ at 22 GHz and 33 GHz, respectively.

Finally, for the comparison of the magnetic field orientation with the molecular gas distribution, we used archival ALMA observations of the CO(3-2) emission in NGC 253 (project code: 2015.1.00274.S), originally presented by [Leroy et al. \(2018\)](#). Of the available data, we selected those obtained with a compact configuration providing a resolution of 0.3×0.4 arcsec, very similar to that of our full polarisation data in Band 7.

3.6 Polarisation and magnetic field maps

Our final images of the polarised intensity and polarisation fraction at both ALMA bands at their native resolution are shown in the upper panels of Figures 3.3 and 3.4, respectively. The upper panels of Figure 3.5 show the orientation of the magnetic field on the plane of the sky, computed by rotating the polarisation angle (PA) by 90° . For each polarisation quantity, we also show the corresponding S/N map, computed using the uncertainty σ defined in Section 3.4. In the lower panel of each Figure, red empty histograms indicate the distribution of pixels with S/N in total intensity above 3. The green and blue solid histograms represent the distribution of pixels after applying an additional threshold on the corresponding polarisation quantity of 1-sigma and 3-sigma, respectively.

3.6.1 Polarised intensity and polarisation fraction

Figure 3.3 shows the polarised intensity of the galaxy at Band 4 and Band 7, for all map pixels with a $I/\sigma_I > 3$. The white vectors represent the orientation of the magnetic field on the plane of the sky. For clarity, one vector is shown every two pixels (for Band 4 maps) and three pixels (for Band 7 maps).

In Band 4, the median value of the polarised intensity is ≈ 0.96 MJy/sr with a standard deviation of ≈ 0.51 MJy/sr, measured over a region where $I/\sigma_I > 3$ and $PI/\sigma_{PI} > 3$. The PI map shows local maxima of $PI \sim 2.5$ MJy/sr from four elongated bright spots situated to the north, south, east and west of the galaxy centre (from here after referred to as PI_N , PI_S , PI_E and PI_W). These maxima (identified in Figure 3.10)

do not have counterparts in total intensity.

The Band 7 observations access smaller physical scales within the starburst region. At this band, the polarised intensity distribution is more uniform, with a median of ≈ 40.28 MJy/sr and standard deviation of ≈ 13.22 MJy/sr (again considering only pixels with $I/\sigma_I > 3$ and $PI/\sigma_{PI} > 3$). The north and south elongated bright spots visible in Band 4 are resolved into several smaller local maxima with $PI \sim 50$ MJy/sr. Particularly noteworthy are three of these maxima, two to the north and one to the south, which achieve values surpassing 80 MJy/sr. As for the Band 4 data, these local maxima do not clearly correspond to structures observed in total intensity.

Figure 3.4 shows the PF maps measured in Band 4 and Band 7, superimposed with vectors that represent the orientation of the magnetic field. As in Figure 3.3, signal-to-noise maps and histograms of the PF pixel values are also shown. The PF distribution measured in Band 4 with $I/\sigma_I > 3$ and $PF/\sigma_{PF} > 3$ has a median value of $\approx 1.69\%$ and standard deviation of $\approx 2.47\%$. Low PF values are concentrated in the innermost region (where the elongated bright spots in PI are located). This inner low PF area (with a median value of around 0.5%), coincides roughly with the region characterised by $I/\sigma_I > 3$ in Band 7.

The higher resolution of the Band 7 data allows us to study the distribution of PF in this region at spatial scales of ~ 5 pc. The median computed with $I/\sigma_I > 3$ and $PF/\sigma_{PF} > 3$ is 1.06% with standard deviation of 0.90%. The map is not uniform, with several local minima apparently aligned along the galaxy midplane in the NE-SW direction.

In regions where $I/\sigma_I > 3$ and $PF/\sigma_{PF} > 3$ the minimum values of PF are 0.15% in Band 7 and 0.09% in Band 4. These values are comparable to the nominal ALMA minimum detectable degree of linear polarisation of 0.1%³.

3.6.2 Magnetic field orientation

In Figure 3.5, we show maps of the magnetic field orientation as projected in the plane of the sky inferred from the Stokes Q and U of Band 4 and Band 7 images. The magnetic field orientation is also shown as white vectors overlaid over the PI, and PF maps in Figures 3.3, and 3.4 in correspondence of pixels where $PI/\sigma_{PI} > 3$.

The magnetic field structure probed by Band 4 observations is characterised by two main ordered components, one parallel to the mid-plane and one perpendicular to it. The two components meet in the central region of the galaxy, where the total intensity distribution observed in Band 4 peaks. A similar configuration has been seen in other

³<https://almascience.eso.org/documents-and-tools/cycle11/alma-technical-handbook>

edge-on galaxies at larger scales (~ 0.1 -1 kpc, Krause et al., 2020, 2006). The magnetic field component parallel to the disk may be driven by the large-scale galactic magnetic field, while the perpendicular component is likely driven by the galactic outflow pushed away by the starbursts activity.

The north and south maxima in the PI map align with areas where the magnetic field is perpendicular to the midplane. We discuss these regions in more detail in Section 3.7.

The orientation of the magnetic field inferred from the Band 7 observations appears more chaotic than at Band 4. The histogram of inferred magnetic field angles nonetheless indicates two main components that are parallel and perpendicular to the galactic midplane. This is evident in the red histogram ($I/\sigma_I > 3$) in the bottom right panel of Figure 3.5, where a prominent magnetic field component with angle $\sim 50^\circ$ can be seen, as well as a broader peak with angles ranging from -80° to -30° . This perpendicular component becomes a more obvious peak $\sim -30^\circ$ when we restrict our comparison to pixels with $I/\sigma_I > 3$ and $PA/\sigma_{PA} > 3$ (blue histogram in the right panel of Figure 3.5).

We note that the magnetic field orientation that we infer in NGC 253 differs from the Central Molecular Zone in our Galaxy. Both the Planck data at 850 GHz and the PILOT balloon-borne data at $240 \mu m$ (Mangilli et al., 2019) indicate a homogeneous magnetic field orientation that is tilted with respect to the Galactic plane by $\simeq 22^\circ$. This difference could be explained by the different viewing angle or by the vastly different star formation efficiency which characterises the central regions of NGC 253 and the Milky Way. Signs of a parallel and perpendicular magnetic field component have been observed at $214 \mu m$ by the FIREPLACE survey (Butterfield et al., 2024; Paré et al., 2024).

3.6.3 Polarisation angle dispersion function

From the polarisation maps we also constructed a map of the polarisation angle dispersion function, $\mathcal{S}$, following Kobulnicky et al. (1994) and Hildebrand et al. (2009). The dispersion function at a given position $\mathbf{x}$ and lag l is defined as

$$\mathcal{S}(\mathbf{x}, l) = \left[\frac{1}{N(l)} \sum_{i=1}^{N(l)} (PA(\mathbf{x}) - PA(\mathbf{x} + \mathbf{l}_i))^2 \right]^{1/2}, \quad (3.5)$$

where $PA(\mathbf{x})$ and $PA(\mathbf{x} + \mathbf{l}_i)$ are the polarisation angles at the central position and at neighbouring positions separated by a vector $\mathbf{l}_i$ whose length lies within an annulus of radius l and width δl . In practice, we compute $\mathcal{S}$ as the median angular difference between a central pixel and all surrounding pixels within such an annulus.

The polarisation angle dispersion function quantifies the local coherence of the plane-of-sky magnetic-field orientation on the spatial scale l . Small values of $\mathcal{S}$ indicate smoothly varying and well-ordered magnetic-field orientations, while large values trace rapid changes of polarisation angle and therefore a locally disordered or strongly perturbed field (Alina et al., 2016).

We construct $\mathcal{S}$ maps in order to identify spatial variations in the degree of magnetic-field ordering and to highlight sharp transitions between neighbouring regions characterised by distinct but internally coherent polarisation orientations. The dispersion function provides a scale-dependent and model-independent diagnostic of magnetic-field structure, allowing us to distinguish smoothly ordered regions from zones where the field is locally distorted, for example by turbulence, feedback, or strong velocity shear.

Maps of the polarisation angle dispersion function $\mathcal{S}$ for our Band 4 and Band 7 ALMA data are shown in Fig. 3.6. We adopt a fiducial lag and annulus width equal to half of the major axis of the clean beam, $l = \delta l = 0.5 \theta_{\text{maj}}$ (i.e. $l = \delta l = 0.15''$ for Band 7 and $l = \delta l = 0.70''$ for Band 4). This choice probes the coherence of the magnetic-field orientation on the smallest spatial scale that is robustly resolved by the observations, while avoiding sub-beam sampling where neighbouring pixels are strongly correlated by the instrumental response. Uncertainties on $\mathcal{S}$ are computed following Eq. (9) of Planck Collaboration et al. (2015a).

The sensitivity of the derived dispersion-function maps to the adopted lag is discussed in Appendix B3, where we show that the main morphological features are preserved for a range of lag values around the fiducial choice.

At Band 4, we identify three quasi-filamentary features with high $\mathcal{S}$ values ($\sim 50^\circ$; red regions in Fig. 3.6) radiating from the centre of the starburst region (SC; Sect. 3.7), where polarisation orientations approximately parallel and perpendicular to the disk meet. These high- $\mathcal{S}$ features (hereafter $\mathcal{S}$ filaments) separate more extended regions characterised by nearly uniform polarisation angles (blue regions in Fig. 3.6).

At Band 7, the $\mathcal{S}$ distribution is more complex, forming an intricate network of $\mathcal{S}$ filaments across the region with robust polarisation detections. As in Band 4, these filaments delineate boundaries between neighbouring areas with distinct but internally homogeneous polarisation orientations.

The complex network of $\mathcal{S}$ filaments seen at Band 7 is only partially recovered at Band 4, primarily in the form of an extended high- $\mathcal{S}$ structure roughly parallel to the galaxy major axis. Owing to the lower angular resolution of the Band 4 data, most of the smaller-scale structures observed at Band 7 are not discernible at that frequency.

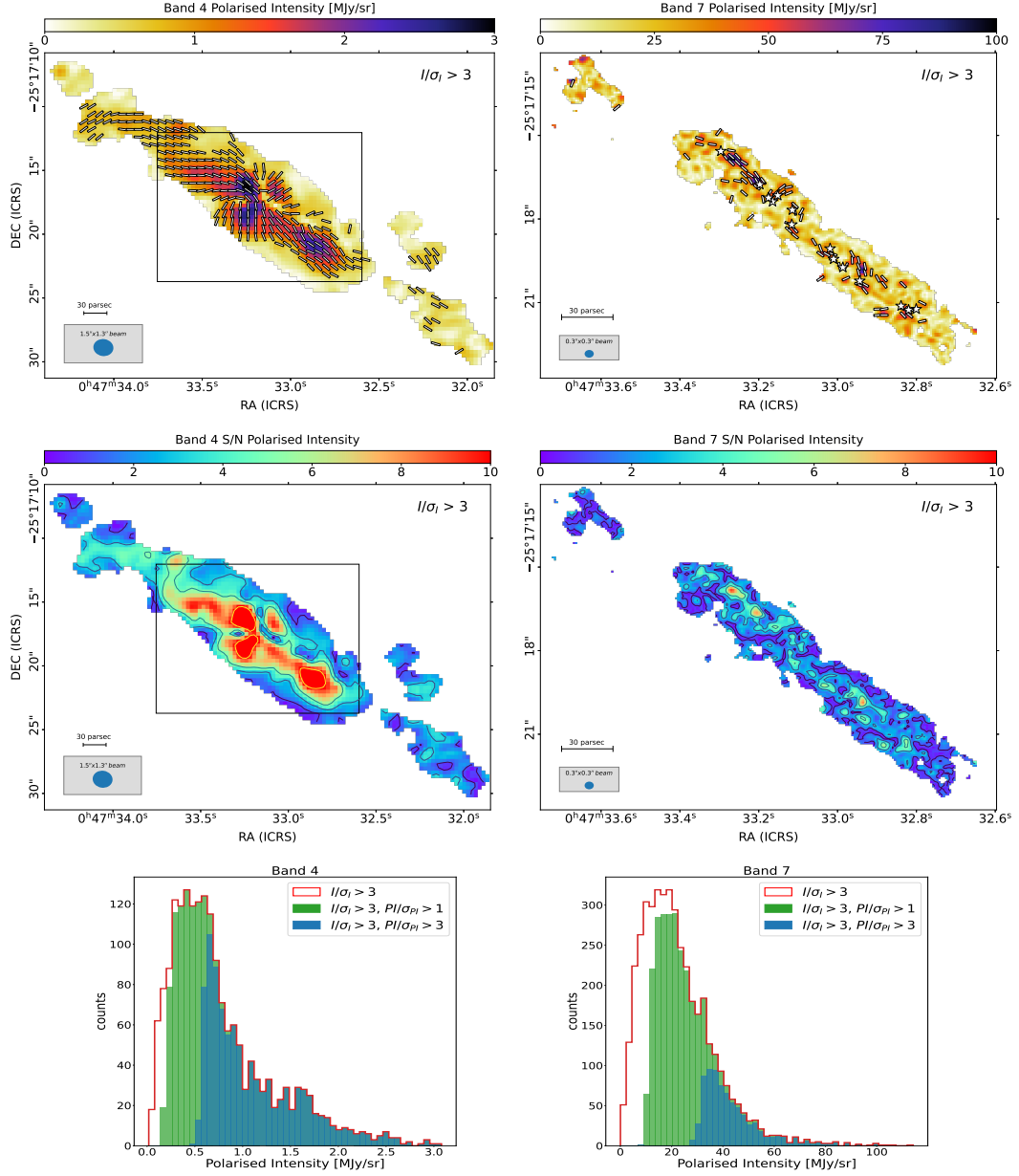


Figure 3.3. Polarised intensity in the centre of NGC 253. *Upper panels:* Maps of the linearly polarised intensity. The vectors indicate the magnetic field orientation and are displayed only at pixels where $PI/\sigma_{PI} > 3$. *Centre panels:* S/N maps of the polarised intensity with contours corresponding to $[1, 3, 5, 10] \times PI/\sigma_{PI}$. White stars in the lower left panel indicate the positions of the SSCs catalogued by Leroy et al., 2018. The synthesised beam of the data is indicated in the bottom left corner, and the pixel selection threshold is shown in the top right corner. Both maps have been obtained selecting pixels with total intensity above 3σ . *Bottom panels:* Histograms of polarised intensity pixel values in the map. The empty histogram shows the distribution of pixels with total intensity above 3σ , while the solid green and blue histograms are the distribution of pixels with polarised intensity above 1σ and 3σ , respectively. The Band 4 and Band 7 results are shown in the top row and the bottom row, respectively.

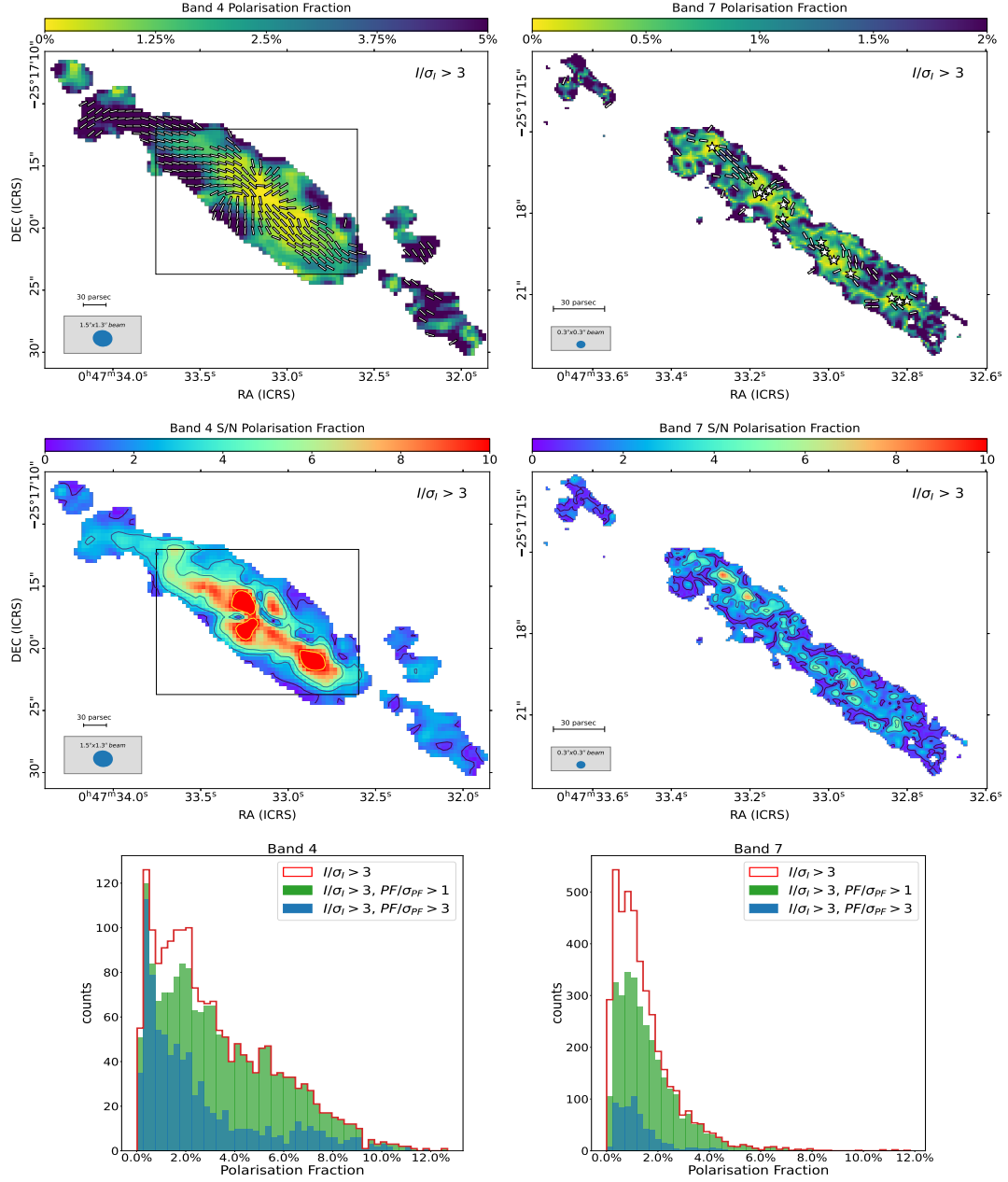


Figure 3.4. Polarisation fraction in the centre of NGC 253. *Upper panels:* Maps of the polarisation fraction. The vectors indicate the magnetic field orientation and are displayed only at pixels where $PI/\sigma_{PI} > 3$. *Centre panels:* S/N maps of polarisation fraction with contours corresponding to $[1, 3, 5, 10] \times PF/\sigma_{PF}$. White stars in the lower left panel indicate the positions of the SSCs catalogued by Leroy et al., 2018. Both maps have been obtained selecting pixels with total intensity above 3 sigma. *Bottom panels:* Histograms of the polarisation fraction pixel values in each map. The Band 4 and Band 7 results are shown in the left column and the right column, respectively. The plot annotations and pixel selection criteria are the same as in Figure 3.3.

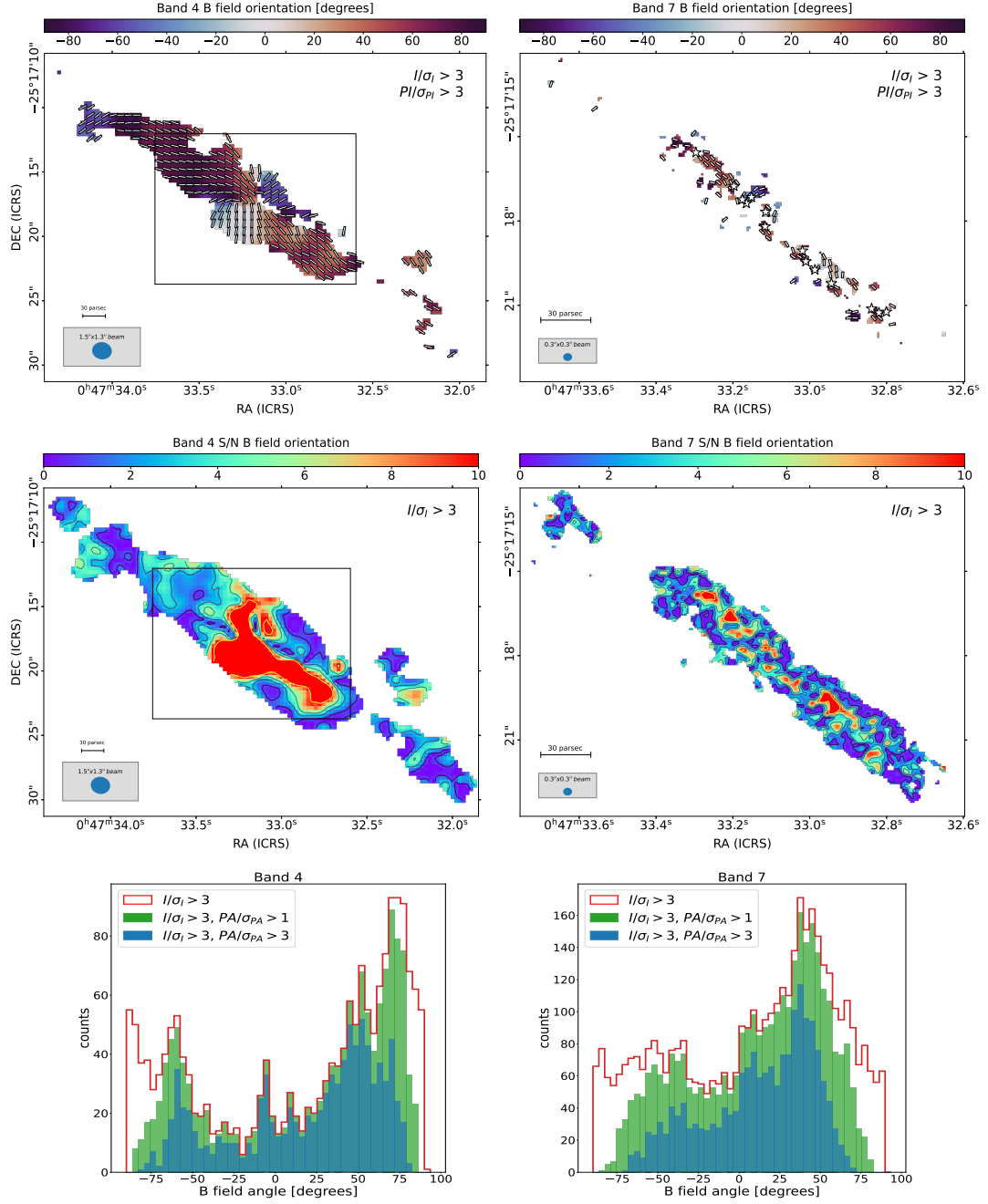


Figure 3.5. Magnetic field orientation in the centre of NGC 253. *Upper panels:* Maps and corresponding vectors of the magnetic field orientation, obtained rotating the observed polarisation angle by 90 degrees. Magnetic field orientation values and vectors are displayed only at pixels where $PI/\sigma_{PI} > 3$. *Centre panels:* S/N maps of the magnetic field orientation with contours corresponding to $[1, 3, 5, 10] \times PA/\sigma_{PA}$. White stars in the lower left panel indicate the positions of the SSCs catalogued by Leroy et al., 2018. Both maps have been obtained selecting pixels with total intensity above 3 sigma. *Bottom panels:* Histograms of the magnetic field orientation pixel values in each map. Results from Band 4 and Band 7 observations are shown in the top row and the bottom row, respectively. The plot annotations and pixel selection criteria are the same as in Figure 3.3.

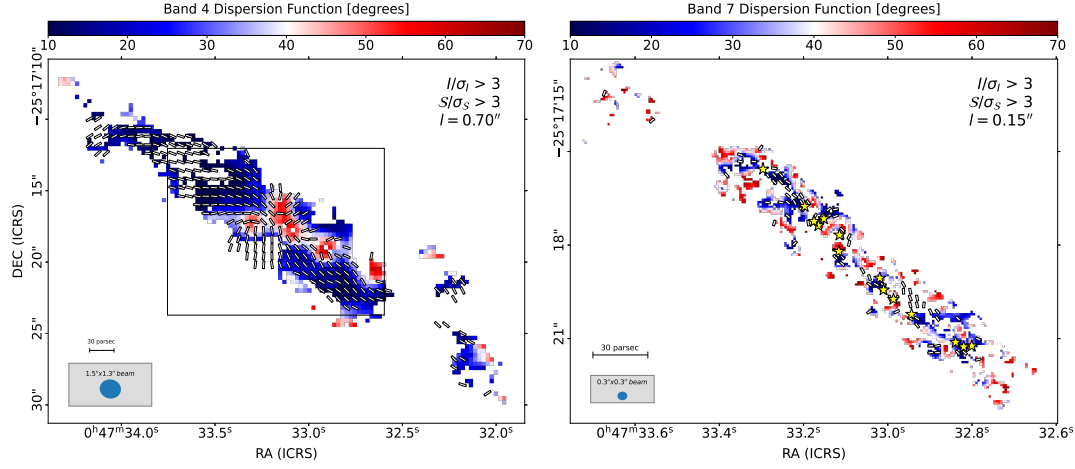


Figure 3.6. Polarisation angle dispersion function in the centre of NGC 253. Maps of the polarisation angle dispersion function obtained using the Band 4 (left) and Band 7 (right) data. Only pixels with $I/\sigma_I > 3$ and $S/\sigma_S > 3$ are shown. Vectors indicating the orientation of the magnetic field vectors are overlaid only in correspondence of pixels where $PI/\sigma_{PI} > 3$. Yellow stars indicate the positions of the SSCs catalogued by [Leroy et al., 2018](#).

3.6.4 Polarisation images at matched resolution

Measurements of polarisation properties strongly depend on resolution. To compare the results at different frequencies, we brought both images to the native resolution of the Band 4 data: $1.5'' \times 1.3''$. Figure 3.7 shows the resulting PF , $\mathcal{S}$ and S/N of PF maps at both bands, overlaid with the magnetic field orientation. The images have been masked to show only pixels characterised by $I/\sigma_I > 3$ in Band 7 at native resolution, while only B-filed vectors corresponding to regions where $PI/\sigma_{PI} > 3$ in both Band 4 and Band 7 are shown. The PF values of the smoothed Band 7 data have been debiased using the covariance matrix computed from the smoothed Stokes I, Q and U maps, following the same process described in Section 3.4. The resulting median and standard deviation values of I, PI , PF , magnetic field orientation and $\mathcal{S}$ maps are summarised in Table 3.4.

Considering only pixels with $I/\sigma_I > 3$ and $PF/\sigma_{PF} > 3$, the PF distribution of the two images at common resolution is characterised by a median PF of 0.49 % for Band 4 and 0.39 % for Band 7. The overall PF configuration is similar in both bands when examined at the same resolution: the observed region appears more polarised at the edges of the mask, showing very low PF to the left and right of the galaxy's centre.

The median values of $\mathcal{S}$ measured at the same resolution are 27.15 degrees in Band 4 and 32.87 degrees in Band 7, indicating that there is still a slightly greater dispersion of

Quantity		$1.5'' \times 1.3''$		$2'' \times 2''$	
		Band 4	Band 7	Band 4	Band 7
I [MJy/sr]	median	318.65	1936.09	361.00	1637.37
	std	268.82	1028.43	222.36	670.13
PI [MJy/sr]	median	1.92	8.86	1.46	4.01
	std	0.51	2.40	0.39	1.85
PF [%]	median	0.49	0.39	0.31	0.22
	std	0.90	0.16	0.81	0.13
B field [degrees]	median	47.93	46.44	44.74	35.04
	std	31.49	27.11	20.05	20.11
S [degrees]	median	27.15	32.87	13.43	26.12
	std	12.55	11.51	15.38	15.95

Table 3.4. Median and standard deviation values of key polarisation quantities. These measurements have been computed using our total intensity and polarisation images of NGC 253 at common resolution. The measurements are made using the area defined in Section 3.6.4. Additionally, for PI , PF , $\mathcal{S}$ and magnetic field orientation only pixels with $PF/\sigma_{PF} > 3$ have been used for the median and standard deviation computation.

the polarisation angles in Band 7. Overall, however, the $\mathcal{S}$ maps at matched resolution are very similar, with local maxima situated in roughly the same regions of our observed field.

For the SED analysis, we smoothed the Band 4 and Band 7 images to $2.2 \times 2.2''$, corresponding to the resolution of the ancillary data described in Section 3.5. At this lower resolution, the median PF is 0.31% for Band 4 and 0.22% for Band 7. The decline in median PF with the increasing size of the observational beam is likely the result of beam depolarisation. This occurs when the polarisation and magnetic field structures are smaller than the observational beam, such that the combination of their heterogeneous polarisation angles yields a net polarisation lower than the intrinsic value at smaller scales.

The distributions of polarisation fraction pixel values in the Band 4 and Band 7 maps at the two matched resolutions ($1.5 \times 1.3''$ and $2.2 \times 2.2''$) are shown in Figure 3.8. When smoothed to the same resolution, the PF distribution peaks at $\sim 0.3\% - 0.5\%$ at both frequencies. The Band 4 distributions, however, show an extended tail of pixels with higher PF values. The pixels with high PF are mostly located in the SW edge of the regions where we have robust polarisation measurements (see Figure 3.7). We discuss this feature further in Section 3.7.

The magnetic field orientation inferred at both common resolutions is also very similar in the two bands. The histograms of the orientation of the magnetic field (bottom panels of Figure 3.8) peak strongly near $\sim 50^\circ$, indicating a component parallel to the

galaxy midplane (characterised by a position angle of $52^\circ \pm 1^\circ$, [Lucero et al. \(2015\)](#)), with a weaker peak in both bands at $\sim -60^\circ$, roughly orthogonal to the plane. From Figure 3.7, it is evident that this perpendicular component is located in the same region at the two bands, corresponding to the local maximum of Band 4 total intensity.

The PF and magnetic field orientation distributions at the two bands at the same resolution do not show significant differences over most of the region that we analyse. The differences in the PF and magnetic field orientation distributions that are evident in Figures 3.4 and 3.5 are lost when the images are convolved to a larger beam, meaning that Band 4 and Band 7 observations probe similar magnetic field and polarisation structures at $1.3''$ scales (~ 25 pc).

3.7 Disentangling the contribution of Synchrotron and Dust

The differences observed in the native resolution polarisation measurement at Band 4 and Band 7 are at least partially the result of the difference in resolution between the two bands. Nevertheless, the two bands may also trace different components of the ISM. The total intensity ratio between Band 4 and Band 7 in our spatially resolved data is higher than what we would expect from thermal dust emission. This indicates an additional emission component in Band 4. Previous analysis of the galaxy emission with multi frequency data also suggested a complex situation in terms of contribution of different emitting mechanisms. [Peel et al. \(2011\)](#) used data over the whole galaxy to determine a global spectral energy distribution (SED), which suggested the presence of free-free, dust and synchrotron emission across the 10 – 100 GHz range in the starburst region of the galaxy. Previous ALMA observations of the 99 GHz continuum and $H40\alpha$ emission with a spatial resolution of ~ 30 pc in the central region indicated that free-free emission with an electron temperature $T_e = 3700 - 4500$ K contributes $\sim 70\%$ to the total flux at $\nu = 99$ GHz ([Bendo et al., 2015](#)). In [Humire et al., 2025](#) a detailed SED-fitting analysis spanning from near-UV to cm wavelengths was performed targeting at a resolution of ~ 50 pc, revealing contributions of synchrotron, free-free and dust emission in the central molecular zone. Higher resolution observations at spatial scales of ~ 5 pc showed a complex situation in which the relative contributions of dust, synchrotron and free-free vary spatially across the starburst region ([Mills et al., 2021](#)).

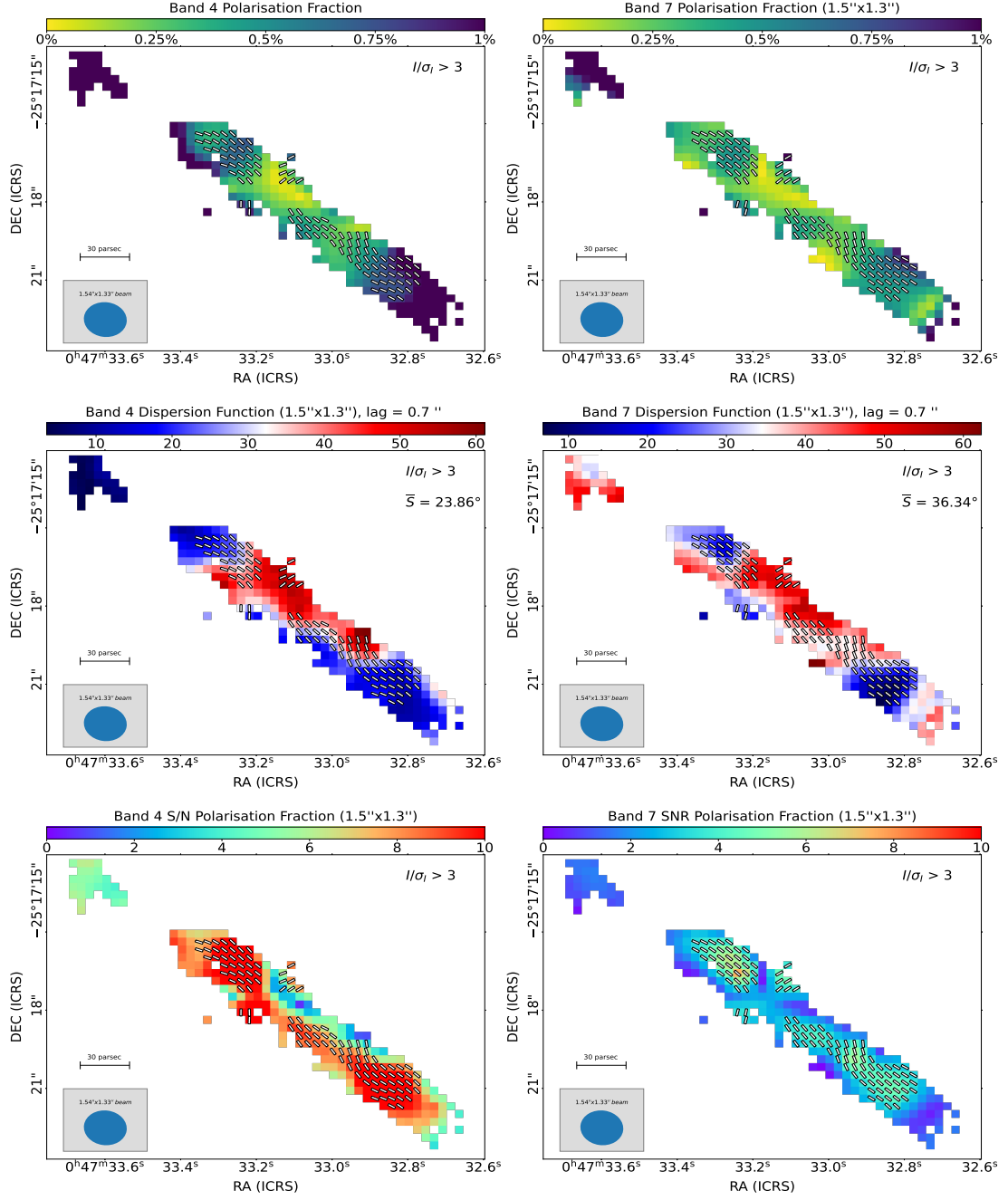


Figure 3.7. Polarisation properties in the centre of NGC 253 measured at the same resolution. Band 4 (left) and Band 7 (right) polarisation fraction (up), $\mathcal{S}$ (centre) and S/N of PF (bottom) maps at the common resolution of $1.5 \times 1.3''$. In all panels, the inferred magnetic field orientations are indicated with white vectors in correspondence of pixels where $PI/\sigma_{PI} > 3$ in Band 7. The images only show the central starburst region, inside the mask constructed from Band 7 data at its native resolution that includes pixels with $I/\sigma_I > 3$.

Band	Centre frequency [GHz]	Angular resolution ["]	MRS ["]	Project code
VLA				
L	1.499	1.61	36	AU30
L	1.499	2.2	36	AU30
C	4.985	1.0	8.9	VAH37
X	8.439	0.63	17	TEST ^a
Ku	14.94	0.54	12	AU36
K	23.870	0.21	2.4	16B337
Ka	36.1693	0.096	1.6	16B337
ALMA				
3	104.264	1.672	18.547	2016.1.00292.S
4	145.0	1.76	17.9	This work
5	179.849	0.946	10.101	2017.1.00028.S
5	193.003	1.11	11.463	2018.1.00162.S
5	196.392	1.175	11.94	2018.1.00162.S
5	199.702	1.316	12.553	2018.1.00162.S
5	203.057	1.19	10.96	2018.1.00162.S
6	265.669	0.967	9.675	2017.1.00161.L
6	234.469	0.907	11.457	2013.1.00099.S
7	295.572	0.892	8.882	2017.1.00161.L
7	289.255	0.868	8.1	2017.1.00161.L
7	285.891	0.923	8.965	2017.1.00161.L
7	282.344	0.93	9.24	2017.1.00161.L
7	343.5	0.3	3.8	This work
7 ^b	345.141	0.43	9	2015.1.00274.S

^a The data have been taken during a TEST run on Jul 3th 1990.

^b This dataset contains the CO(3-2) line emission, used in Section 3.8.2.

Table 3.5. Data used for the SED analysis in Section 3.7. The continuum images have been gathered through the VLA and ALMA public archives. Columns report the band name, the central frequency, the native angular resolution and maximum recoverable scale (MRS) and the project code of the data.

Measured Values		Fit results with $\alpha_{ff} = 0.118$, $T_d = 30$ K and $\alpha_{syn} = [-0.45, -0.75]$											
		Band 7						Band 4					
Region	$\mathbf{PF_{meas, Band 7}} [\%]$	$\mathbf{PF_{meas, Band 4}} [\%]$	I_{dust}/I_{tot}	I_{syn}/I_{tot}	I_{ff}/I_{tot}	I_{dust}/I_{tot}	I_{syn}/I_{tot}	I_{ff}/I_{tot}	χ^2_{red}	$\mathbf{PF_{dust}} [\%]$	$\mathbf{PF_{syn}} [\%]$	$\frac{PF_{syn}}{PF_{dust}}$	
SA	0.31	0.55	[0.89, 0.91]	[0.03, 0.01]	[0.08, 0.08]	[0.22, 0.32]	[0.26, 0.14]	[0.51, 0.55]	[0.10, 0.07]	[0.25, 0.27]	[1.78, 3.44]	[7.2, 12.7]	
SC	0.10	0.17	[0.80, 0.82]	[0.04, 0.01]	[0.16, 0.17]	[0.06, 0.13]	[0.21, 0.08]	[0.73, 0.79]	[0.03, 0.04]	[0.08, 0.09]	[0.83, 2.37]	[11.0, 26.8]	
SO	0.32	0.58	[0.91, 0.93]	[0.03, 0.01]	[0.06, 0.06]	[0.31, 0.42]	[0.29, 0.16]	[0.40, 0.42]	[0.12, 0.09]	[0.27, 0.29]	[1.78, 3.29]	[6.6, 11.3]	
PI_E	0.29	0.44	[0.90, 0.91]	[0.02, 0.01]	[0.08, 0.08]	[0.26, 0.34]	[0.21, 0.10]	[0.54, 0.56]	[0.08, 0.05]	[0.29, 0.31]	[1.65, 3.36]	[5.7, 11.0]	
PI_S	0.30	0.60	[0.77, 0.79]	[0.04, 0.01]	[0.19, 0.20]	[0.04, 0.08]	[0.20, 0.11]	[0.76, 0.81]	[0.07, 0.05]	[0.27, 0.32]	[2.86, 5.60]	[10.5, 17.7]	
PI_W	0.47	0.70	[0.94, 0.95]	[0.01, 0.01]	[0.04, 0.04]	[0.41, 0.49]	[0.19, 0.10]	[0.40, 0.42]	[0.11, 0.08]	[0.44, 0.46]	[3.71, 7.37]	[8.5, 16.1]	

Table 3.6. SED-fitting results for the different regions analysed in Band 7 and Band 4. For each band, the actual $\mathbf{PF_{meas}}$ values measured from the data are reported in bold in the columns 2-3, while the columns 4-9 report the range of values of the relative contribution of dust, synchrotron, and free-free to the total intensity. These values are obtained from the SED-fitting, assuming as synchrotron spectral α_{syn} the values $\alpha_{syn} = 0.45$ and $\alpha_{syn} = 0.75$. Column 10 reports the resulting fitted value of the emissivity index β_d , while column 11 reports the range of values of the reduced χ^2 of the fits. The dust polarisation fraction $\mathbf{PF_{dust}}$ and the synchrotron polarisation fraction $\mathbf{PF_{syn}}$ derived (see Section 3.7 for more details) are reported in the columns 12 and 13. The last column report the ratio of the derived polarisation fractions of the synchrotron and dust components. The regions in the first column are described in details in Section 3.7 and indicated in Figure 3.10.

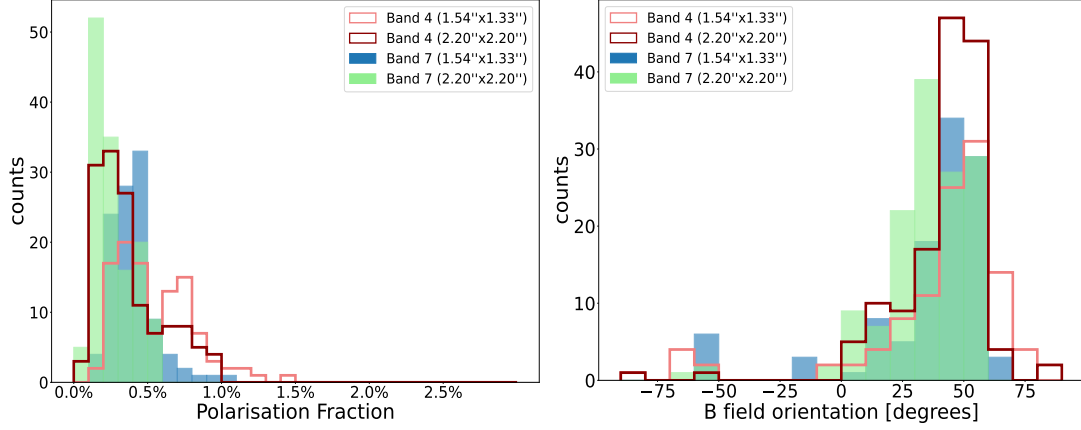


Figure 3.8. Polarisation properties in the centre of NGC 253 measured at the same resolution. Distributions of pixel values of the polarisation fraction (left panel) and magnetic field orientation (right panel). Empty histograms represent the distributions of Band 4 pixels in the images at $1.5 \times 1.3''$ (pink) and at $2.2 \times 2.2''$ resolutions (red). The solid blue and green histograms represent the distributions at Band 7. Only pixels with $S/N \text{ } PF/\sigma_{PF} > 3$ have been used for the computation of the histograms.

3.7.1 Estimating the Band 4 emission components

In order to estimate the relative contribution of the different emission mechanisms to the polarisation fraction observed in Band 4, we analysed the total intensity spectral energy distribution (SED) of the target, collecting archival data in the frequency range 1 – 350 GHz (see Table 3.5 for details about the archival data used). All images were convolved to a $2.2''$ round beam, corresponding to the largest beam of the available archival data, and regridded to have common pixelisation.

The SED-fitting was performed using the public code DustEMWrap (Compiègne et al., 2011)⁴. We constructed input SEDs using our full observed region, as well as a few regions with exceptional polarisation properties or intensities (see below for precise definitions). Our model fits describe the thermal dust emission using a Modified Black Body (MBB) and allow for contributions from synchrotron and free-free emission using the plugins provided in DustEMwrap. Since there are not noticeable signs of anomalous microwave emission (AME), we exclude any possible contribution from spinning dust. The absence of significant AME emission in NGC 253 is also suggested in (Mills et al., 2021) and (Peel et al., 2011).

The mask used for the SED-fitting of the whole emission has been defined as the largest mask that includes pixels with $I/\sigma_I > 3$ in all archival images. This region is

⁴<http://dustemwrap.irap.omp.eu/>

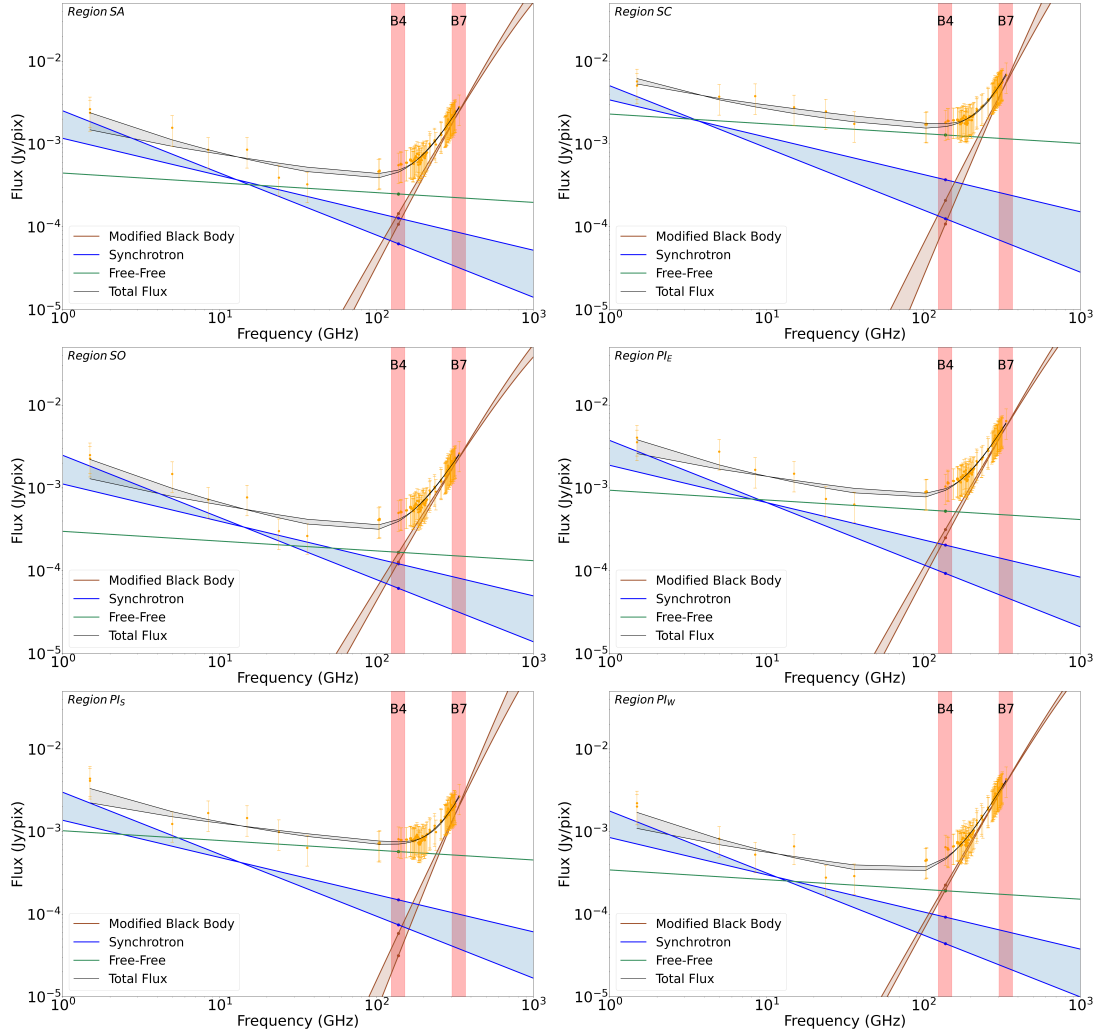


Figure 3.9. SED-fitting analysis. The panels show the SED decomposition for the different regions (indicated in the top-left corner) discussed in Section 3.7. The observed measurements, shown by orange points with their uncertainties ($\pm 3\sigma$) have been modelled using DustemWrap. The three fitted components: dust (in orange), synchrotron (in blue), and free-free (in green) are shown with shaded area indicating their range, assuming two different spectral index values.

labelled SA in Figure 3.10 and shown in pink contours. The variances used for the SED-fitting process are all assumed to be $0.4 \times I^2$, where I is the total intensity of the corresponding data point.

Due to the degenerate contributions of the three processes in the frequency range 1 – 300 GHz, we fixed or restricted the range of several key physical parameters. The spectral index of the free-free emission was set to a fixed value of 0.118, a commonly observed value at sub-millimetre wavelengths (Condon, 1992; Draine, 2011). The temperature of dust emission was assumed to be $T_d = 30\text{ K}$, a reasonable value for the centre of NGC 253 (Melo et al., 2002; Weiß et al., 2008). For the synchrotron spectral index α_{syn} we tested two extreme values: 0.45 and 0.75. These values cover the typical range observed in high-density starburst galaxies (Heesen et al., 2022). The intensities of the dust, synchrotron, and free-free emission and the emissivity index β_d of the MBB were allowed to vary independently during the fit. Table 3.6 reports the results of the SED-fitting, quoted as a range of values obtained when adopting the two extreme values of α_{syn} .

The decomposition obtained for the SED of the whole starburst region is shown in the upper left panel of Figure 3.9. Both fits with $\alpha_{syn} = 0.45$ and $\alpha_{syn} = 0.75$ are shown. The model was able to fit the data with a reduced $\chi^2_{red} = 0.10$ and 0.07, respectively. The β_d values derived from SED-fitting across various regions align with those observed in other starburst galaxies (McKay et al., 2023).

The SED-fitting results for the SA region indicate that the thermal dust emission contributes $\cong 90\%$ of the Band 7 total intensity, while free-free and synchrotron contribute $\cong 8\%$ and $\cong 1\%$ respectively. In the spectral range 10 – 200 GHz, none of the three emission components is negligible. At Band 4, the contribution of dust, synchrotron and free-free emission to the total intensity is 22% – 32%, 26% – 14% and 51% – 55%, respectively.

In order to estimate how the different contributions vary across the central starburst region, we repeated the analysis using a subset of pixels within different areas that are indicated in Figure 3.10. These areas were selected by identifying pixels with elevated values of both total intensity and PI . Specifically, the SC area is defined by selecting the brightest 25% of pixels in the 2.2'' map of Band 4 total intensity. This area corresponds to the region where the parallel and perpendicular components of the magnetic field structure observed in Band 4 converge. The region SO is the complementary region of SC in SA. The areas labelled PI_E , PI_S , and PI_W are identified by selecting the pixels with the highest 25% observed values of polarised intensity at Band 4. The subscripts E, S, and W denote the positions relative to the midplane of the galaxy. The SED

decompositions for these regions are shown in the panels of Figure 3.9. The names of the regions are indicated in the upper left corner of each panel. The SED-fitting results for these subregions are also listed in Table 3.6. The overall trend observed in the SA area is roughly consistent across all other subregions, where Band 4 maps a similar contribution of free-free, synchrotron, and dust emissions, while Band 7 primarily traces dust.

Consistency check: star formation rate from the synchrotron component. As an independent validation of the SED decomposition, we used the synchrotron luminosity inferred for the SA region to estimate the star-formation rate via the non-thermal radio calibration of [Condon \(1992, Eq. 21\)](#). For the SA aperture, corresponding to the central ~ 150 pc, we obtain $\text{SFR}_{\text{Condon}} = 0.19\text{--}0.36 M_{\odot} \text{ yr}^{-1}$, where the range reflects the uncertainty in the adopted synchrotron spectral index ($\alpha_{\text{syn}} = 0.45$ to 0.75). This corresponds to a star-formation rate surface density of $\Sigma_{\text{SFR}} = 10.6\text{--}20.1 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, placing the SA region in the starburst regime.

Free-free and recombination-line measurements yield a total star-formation rate of $\sim 1.5\text{--}2 M_{\odot} \text{ yr}^{-1}$ within the central ~ 300 pc nuclear region of NGC 253 (e.g. [Bendo et al., 2015](#); [Leroy et al., 2015](#)). For the corresponding physical area, this implies a star-formation rate surface density of order $\Sigma_{\text{SFR}} \sim 20\text{--}40 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, depending on the assumed geometry and aperture.

Considering the smaller physical extent of the SA region and the different timescales probed by non-thermal radio emission compared to free-free and recombination-line tracers, the agreement at the order-of-magnitude level supports the physical plausibility of the SED-based separation of synchrotron, free-free, and dust emission components.

3.7.2 Contributions to Band 4 polarisation

The above SED decomposition indicates that free-free emission, which is unpolarised ([Rybicki & Lightman, 1986](#)), dominates the total Band 4 intensity. Our polarisation fraction measurements at Band 4 are thus due to a combination of synchrotron and dust emission, both polarised, diluted by the unpolarised free-free emission. However, we can use our SED decomposition results to estimate the polarisation fractions of the dust and synchrotron emission independently. We assume that only synchrotron and thermal dust contribute to the polarised emission in both ALMA bands.

For synchrotron emission from a power-law electron population, the intrinsic fractional polarisation depends primarily on the electron energy index (equivalently the synchrotron spectral index) and is therefore not expected to vary strongly with observing

frequency across a limited bandpass (see Section 2.3 and e.g. Rybicki & Lightman, 1986). In practice, the dominant source of frequency-dependent changes in observed synchrotron polarisation in galaxies is Faraday rotation and Faraday depolarisation, which exhibit strong wavelength dependences (e.g. Burn, 1966; Sokoloff et al., 1998). At millimetre wavelengths, these Faraday effects are negligible, so we assume that the synchrotron polarisation fraction is the same in Band 4 and Band 7 within each region analysed. We stress that this assumption refers only to the frequency dependence and does not imply spatial uniformity of the synchrotron polarisation fraction, which is observed to vary across galactic disks and halos (e.g. CHANGES results; Mora-Partiarroyo et al., 2019).

Not much is known about possible frequency variations of the thermal dust polarisation fraction. The analysis of the all sky Planck data detected no systematic trend over the range 100-353 GHz, albeit with large uncertainties. Combining this result with very limited observations of specific sky regions in the FIR has led models (e.g., Hensley & Draine, 2021) to assume no spectral variations of the dust polarisation fraction as long as dust particles are large enough to align with the magnetic field. Here we also follow this assumption and assume no frequency variations of the thermal dust polarisation fraction over the range observed with ALMA. Under these assumptions, the observed polarised intensities in Bands 4 and 7 can be written simply as

$$\begin{pmatrix} PI_{B4} \\ PI_{B7} \end{pmatrix} = \begin{pmatrix} I_{syn,B4} & I_{dust,B4} \\ I_{syn,B7} & I_{dust,B7} \end{pmatrix} \times \begin{pmatrix} PF_{syn} \\ PF_{dust} \end{pmatrix}, \quad (3.6)$$

where I_{syn} and I_{dust} are the total intensity of the synchrotron and thermal dust emission, PF_{syn} and PF_{dust} are the polarisation fraction of the synchrotron and dust emission (constant in Band 4 and 7 due to the assumptions we made), and the subscripts B4 and B7 refer to ALMA measurements in Bands 4 and 7, respectively.

The polarisation fractions can be deduced by inverting Equation 3.6, leading to

$$PF_{syn} = \frac{I_{dust,B7} \times PI_{B4} - I_{dust,B4} \times PI_{B7}}{I_{syn,B4} \times I_{dust,B7} - I_{syn,B7} \times I_{dust,B4}} \quad (3.7)$$

$$PF_{dust} = \frac{I_{syn,B4} \times PI_{B7} - I_{syn,B7} \times PI_{B4}}{I_{syn,B4} \times I_{dust,B7} - I_{syn,B7} \times I_{dust,B4}}. \quad (3.8)$$

We measured PI_{B4} and PI_{B7} from the PI maps in Band 4 and Band 7, and derived the PF_{dust} and PF_{syn} using the SED-fitting results for I_{syn} , I_{ff} and I_{dust} for the two bands. Inside the SA mask (pink contour in Figure 3.10), the estimated polarisation fraction for the synchrotron component ranges from $PF_{syn} = 1.78 - 3.44\%$ (depending on the adopted synchrotron spectral index) and the dust polarisation ranges from $PF_{dust} = 0.25 - 0.27\%$. The measured polarisation fraction, which includes

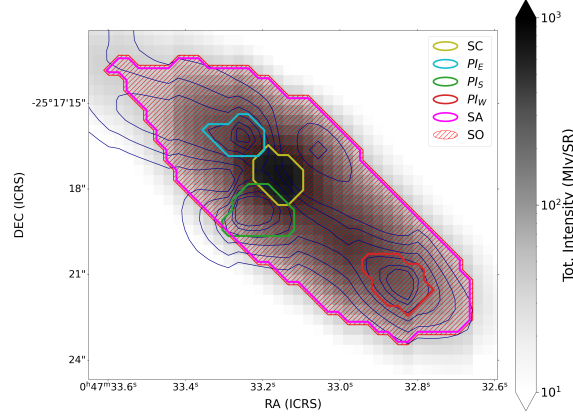


Figure 3.10. Regions used for the SED-fitting analysis. Band 4 images of total (colour scale) and polarised (contours) intensity. The regions analysed in detail in Section 3.7 are indicated.

contributions from both dust and synchrotron components, is $PF_{meas.,B4} = 0.55\%$ at Band 4 and $PF_{meas.,B7} = 0.31\%$ at Band 7.

For all regions where we conducted the SED-fitting, the synchrotron and dust polarisation fractions obtained using the above approach are listed in the last two columns of Table 3.6. The reduced χ^2 of the SED-fittings are also reported.

3.7.3 Variations in the polarisation fraction

The measured polarisation fraction in Band 4 is $\sim 0.50\% - 0.70\%$ across the starburst area, dropping to $\sim 0.17\%$ in the SC region. From our SED-fitting analysis, this corresponds to PF_{dust} of 0.25% for SA and 0.08% for SC. A decrease in the measured PF in sub-mm data is usually attributed to a gradual loss of alignment of dust grains, fluctuations in the orientation of the magnetic field along the line-of-sight (LOS), or tangling of the magnetic fields on scales smaller than the observational resolution, causing depolarisation (Planck Collaboration et al., 2015a). In addition to these effects, the observed decrease of PF in Band 4 can also be attributed to a contamination of non-polarised free-free emission, as our SED-fitting suggests. Interestingly, the decrease in polarisation fraction in the SC region is more pronounced for the dust component compared to the synchrotron component. The ratio between the polarisation fractions of the synchrotron and dust components, $\frac{PF_{sync}}{PF_{dust}}$, is 7-11 in the SO region, but it increases to 11-27 in the SC region. The regions PI_E , PI_S and PI_W are all characterised by a relatively strong synchrotron component of PF. The region PI_S and PI_W are also characterised by a large $\frac{PF_{sync}}{PF_{dust}}$ ratio (around 10-18). This may be linked to the presence

of the extended multi-phase outflow (see Section 3.8.1).

We can summarise the SED-fitting results as follows:

- The different polarisation fractions observed at Band 4 and 7, after being smoothed to the same resolution, can be attributed to the distinct contributions of synchrotron, dust and free-free to the total emission, combined with the different characteristic polarisation fraction of the dust and synchrotron components at these frequencies. At Band 7, the total intensity is dominated by dust, while at Band 4 the emission is mostly due to free-free, with non-negligible, roughly equivalent contributions from dust and synchrotron. The high polarisation fraction of the synchrotron component is likely the main factor behind the higher observed polarisation fraction in Band 4.
- In all the regions, the polarisation fraction of the synchrotron component is higher than that of the dust component. In particular, The ratio between the polarisation fractions of the synchrotron and dust components, $\frac{PF_{sync}}{PF_{dust}}$, is 7.2-12.7 in the region SA, 11.0-26.8 in the SC, 6.6-11.3 in SO, 5.7-11.0 in PI_E , 10.5-17.7 in PI_S and 8.5-16.1 in PI_W .
- The estimated PF_{dust} and measured PF in Band 7 exhibit comparable values. Given the assumption of constant polarisation fraction of both the synchrotron and dust components over the frequency range 100 – 353 GHz, we can deduce that in Band 7 the polarisation fraction is due almost entirely to dust with negligible effect due to synchrotron.
- The inferred magnetic field structure (shown in Figure 3.7) is common to both bands, and thus appears relatively insensitive to the different emission processes that dominate the polarisation in the two bands.
- The depolarisation within the central region (SC) appears to be more pronounced for the dust component than for the synchrotron component. This suggests that the degradation of the alignment of dust grains, contributing to PF_{dust} , may play a role in the observed depolarisation. Multiple phenomena could explain the dust depolarisation in this region, including a differential tangling of the magnetic field between dense and more diffuse part of the LOS.

3.8 Connection with environment

3.8.1 The magnetic field morphology and outflow in the centre of NGC 253

The nuclear starburst of the galaxy NGC 253 is responsible for launching a large multiphase outflow which extends to several kpc. This structure is detected across the electromagnetic spectrum, including X-ray (Strickland et al., 2000; Lopez et al., 2023), ionised gas (Westmoquette et al., 2011), molecular gas (Bolatto et al., 2013b; Krieger et al., 2019) and radio (Heesen et al., 2011).

The morphological structure of the outflow varies significantly depending on the observational wavelength. Optical observations (particularly $H\alpha$) and X-ray observations reveal a prominent biconical morphology that extends to several kpc in the SE and NW directions. From $H\alpha$ kinematic modelling, the opening angle of the outflow is $\sim 60^\circ$ (Westmoquette et al., 2011). Due to the orientation of the galaxy, the SE cone is more prominent and extended than the NW cone.

The molecular phase of the outflow, traced by CO(1-0) and CO(3-2) emission lines, is characterised by a more concentrated structure situated along the edges of the biconical wind. One of the most prominent structures is a south-western (SW) streamer placed along the direction of the minor axis of the starburst region (see e.g. Bao et al., 2024). Enhancements in the CO emission, such as the SW streamer and other distinct features, might be due to individual clouds that are trapped, disrupted, and ejected in the outflow (Zschaechner et al., 2018).

Radio continuum emission indicates the presence of four prominent filaments (scale height of 150 ± 20 pc) surrounding the SE and NW cone (Heesen et al., 2011). In that study, the large scale magnetic field structure was probed by radio polarisation observations at wavelengths of 6 cm and 3 cm, with resolutions of approximately 500 pc and 120 pc, respectively. The large scale magnetic field lines inferred from the radio data slowly open away from the midplane of the galaxy, forming a characteristic X-shaped field centred on the nucleus. The total magnetic field strength measured in the filaments is $46 \pm 10 \mu\text{G}$, with an ordered field strength of $21 \pm 5 \mu\text{G}$, which is high enough to counteract the pressure in the nuclear outflow (Heesen et al., 2011), suggesting a role of the magnetic field in collimating the outflow.

Figure 3.11 shows a three-colour, multi-wavelength view of the central region of NGC 253. The X-ray (blue colour), $[NII]$ emission line (red) and CO(3-2) (green) emissions are shown in relation to the magnetic field structure revealed by our Band 4 ALMA data. The white contours indicate the Stokes I emission in Band 4. The magnetic

field lines inferred from our Band 4 data are shown as white vectors. The vectors are displayed every two pixels and only where $PI/\sigma_{PI} > 3$. The cyan contour highlights the regions that show outflow components, identified using $[NII]$ and $H\alpha$ line integrated intensity from VLT/MUSE data (Cronin et al. in prep.). The SW streamer location, taken from Zschaechner et al., 2018, is indicated as a red arrow and labelled as SW. In Figure 3.12, the upper panel shows the same three-colour image as Figure 3.11 but zoomed in to provide a closer view of the central region, while the lower panel presents the RGB image superimposed with the Band 7 magnetic field vectors. The white stars mark the position of the SSCs identified by Leroy et al., 2018 (see also Levy et al., 2021, 2022; Mills et al., 2021), which account for a large fraction of the star formation activity in the central starburst region. Three of these SSCs (labelled 4, 5 and 14 in Leroy et al., 2018) have been observed to show P-Cygni profiles in multiple lines, which suggest the presence of small outflow activities. Furthermore, some of these SSCs (4, 6, 10, 10NE, 11, 12, and 13) host $H40\alpha$ emission with exceptionally broad linewidths ($\delta v_{FWHM} \sim 100 - 200 \text{ km s}^{-1}$), suggesting that they contribute to driving the ionised component of the multi-phase outflow (Mills et al., 2021).

The base of the ionised component of the biconical outflow is a strong source of X-ray and $[NII]$ emission. The magnetic field inferred from our Band 4 data (Figure 3.11 and upper panel of Figure 3.12) seems to closely track the profile of the base of the outflow: the B-lines start to open away from the midplane at the peak position of the X-ray emission, assuming the same conical structure of the outflow. Away from the base of the outflow towards the SE, the magnetic field lines seem to assume an ordered horizontal position relative to the midplane, until they are disrupted at the position of the SW molecular streamer. The same behaviour is observed on the northern side of the midplane, with the horizontal B-lines being disrupted towards a more vertical orientation along the direction of the SW streamer. The signal-to-noise ratio of our observations decreases away from the midplane. Consequently, it is not possible with our data to determine if the magnetic field structure continues to follow the biconical outflow and align with the SW streamer’s direction.

Both the magnetic field lines and the outflow cone are centred on the SC region defined in Section 3.7. This area is characterised by high molecular gas column density (as traced by the CO(3-2) map), and hosts four of the seven SSCs characterised by broad linewidth $H40\alpha$ emission. In the SC region, the SED-fitting analysis (see Section 3.7) also suggests a high synchrotron polarisation fraction indicating a coherent and ordered magnetic field. A possible interpretation is that the high star formation rate drives the large scale winds which compress and order the magnetic field, aligning it to the outflow

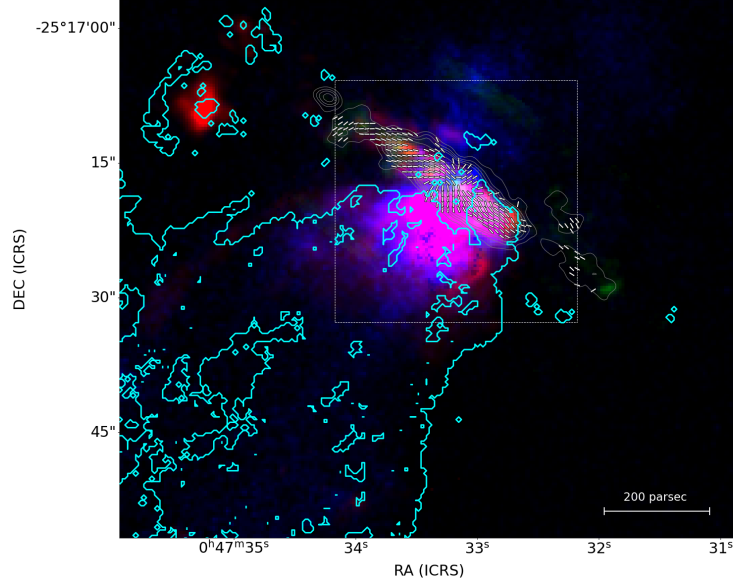


Figure 3.11. Three-colour composite, multi-wavelength view of the central region in NGC 253. Blue, red, and green show the X-ray emission from [Lopez et al., 2023](#), optical $[NII]$ data from Cronin et al. in prep., and CO(3-2) emission from [Leroy et al., 2018](#), respectively. The magnetic field lines and the emission of Stokes I flux of our ALMA Band 4 data are also shown as white vectors and yellow contours, respectively. The vectors are displayed every two pixels and only where $PI/\sigma_{PI} > 3$. The grey contours correspond to $[5, 7, 10, 30, 100] \times \sigma_I$. The white rectangle marks the region shown on the upper panel of Figure 3.12.

cone. This interpretation is coherent with the picture of the SSCs characterised by broad linewidth $H40\alpha$ emission being the main driver of the large scale winds forming the biconical outflow.

The launch location of the wind seems to corresponds roughly to the SC region defined in Section 3.7, which is highlighted as yellow contour in both panels of Figure 3.12. The highly tangled magnetic field lines and the limited area for which we have robust Band 7 polarisation measurements complicate a more detailed comparison between the magnetic field structure and the outflow morphology. From our data, it is not clear if the outflows due to SSCs 4,5 and 14 in ([Levy et al., 2021](#)) have a counterpart in the small scale magnetic field morphology.

All the SSCs show a spatial relation with the measured PF in Band 7. This can be seen in the upper-right panel of Figure 3.4, where the positions of the SSCs are indicated by white stars. Locations with at least one SSC are characterised by local minima in PF measured in Band 7. Measuring the PF within one beam located on the SSCs, we get an average value below 0.4%, compared to a median PF value of 1.06%

across the entire mask with $I/\sigma_I > 3$ and $PF/\sigma_{PF} > 3$. The correlation between local minima in PF and the position of SSCs is part of a more general relation that links the gas column density and polarisation fraction, which we discuss in the next subsection.

3.8.2 The PF vs N_H relation

A trend for the thermal dust polarisation fraction to decrease with increasing gas column density was identified from the all-sky Planck data at 353 GHz (Planck Collaboration et al., 2015a), over a wide range of column densities from 10^{20} to 10^{23} H/cm^2 . This confirmed results from earlier ground-based observations of very bright regions that typically detected low polarisation fractions. Analysis of the Planck data revealed that the PF - N_H anti-correlation extends to dense regions with no star formation. It is important to stress that since polarisation fraction measurements are positively biased upwards by noise and photon noise is always higher in low brightness regions, an anti-correlation can arise due to noise bias only. Therefore, only good quality de-biased polarisation data should be used to address this issue.

The physical origin for the anti-correlation between PF and N_H is not completely clear. As dust alignment with the magnetic field could result from radiative alignment torques (RATs, e.g. Dolginov & Mitrofanov 1976; Andersson et al. 2015), the lack of photons in dark dense clouds could explain the observations. However, since polarisation sums as a spin-2 vector within the observational beam and along the LOS, the observed depolarisation could also result from the tangled structure of the magnetic field in dense regions. Additionally, since all models of dust alignment with the magnetic field predict a better alignment for large dust grains, the observed trend could also result from variations of the grain size distribution with column density. Explanations involving destruction of large dust grains (e.g. Lee et al., 2020; Hoang et al., 2021; Lopez-Rodriguez & Tram, 2024) have been proposed for highly active star-forming regions.

Analysis of the all-sky Planck maps at 350 GHz did not reveal a systematic change in the relationships between the polarisation dispersion angle (see Section 3.6.3) and polarisation fraction with column density, indicating that tangling of the magnetic field is the best explanation for the observed trend over the N_H range sampled by the Planck data (Planck Collaboration et al., 2015a).

We used our debiased polarimetric observations and the archival ALMA observations of the CO(3-2) line (Leroy et al., 2018) to investigate the correlation between the polarisation fraction and the column density in NGC 253. We calculated the column density N_H from the CO(3-2) line fluxes using the relation $N_{H2} = X_{CO} I_{CO(1-0)}$, where X_{CO} is the CO-to- H_2 conversion factor for the CO(1-0) line integrated intensity $I_{CO(1-0)}$

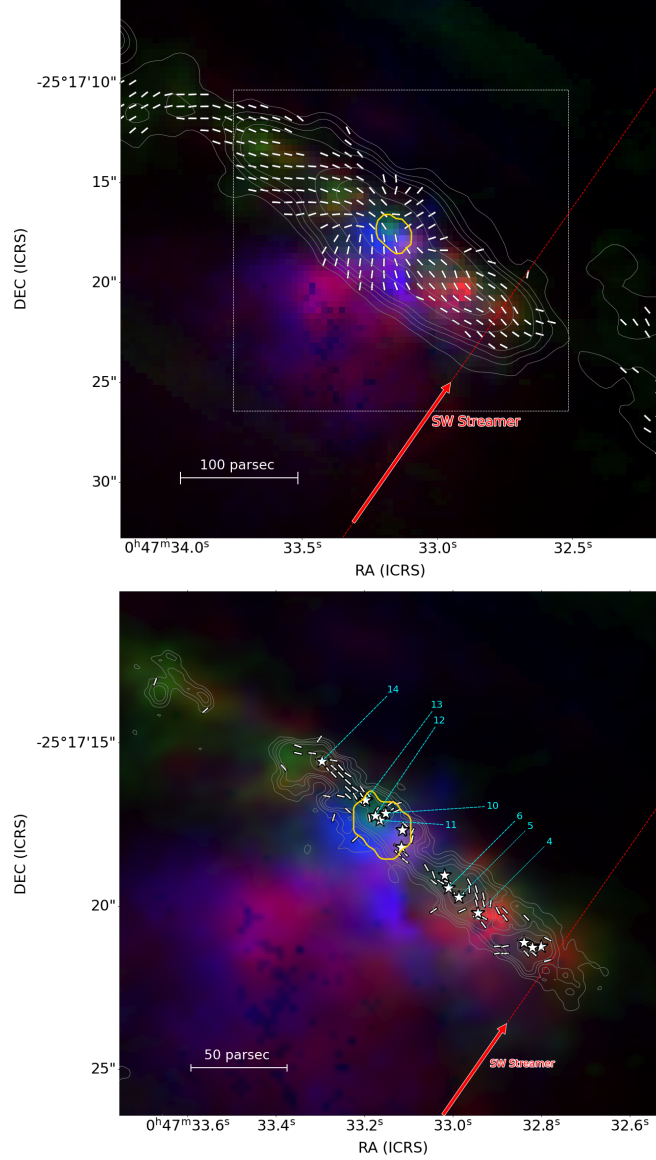


Figure 3.12. Three-colour composite, multi-wavelength view of the central region in NGC 253. Blue, red, and green show the X-ray emission from [Lopez et al., 2023](#), optical $[NII]$ data from [Cronin et al. in prep.](#), and CO(3-2) emission from [Leroy et al., 2018](#), respectively. The magnetic field lines and the emission of Stokes I emission of our ALMA Band 4 data (upper panel) and Band 7 data (lower panel) are also shown as white vectors and yellow contours, respectively. The vectors are displayed every two pixels and only where $PI/\sigma_{PI} > 3$. The grey contours correspond to $[5, 7, 10, 30, 100] \times \sigma_I$. The red arrow marks the position of the molecular south-western streamer. The white rectangle on the upper panel marks the region shown on Figure 3.11. The SSCs are marked as white stars and labelled following the notation of [Leroy et al., 2018](#). The yellow contour mark the position of the SC region defined in Section 3.7.

(Bolatto et al., 2013a). We converted $I_{CO(3-2)}$ to $I_{CO(1-0)}$ using the empirical line ratio $r_{31} = \frac{I_{CO(3-2)}}{I_{CO(1-0)}}$. We adopted $X_{CO} = 0.5 \cdot 10^{20} [K km s^{-1} cm^{-2}]$, a value consistent with other estimates for starburst galaxies (Bolatto et al., 2013a). Following Schinnerer & Leroy, 2024 we assumed $r_{31} = 0.31$. We then estimated N_H assuming $N_H \approx 2N(H_2)$.

Figure 3.13 shows the observed relation between PF and N_H in our data computed at Band 4 (upper panel) and Band 7 (lower panel). The CO(3-2) data were convolved to the same resolution as the ALMA data, and only pixels with good S/N in CO(3-2) intensity ($S/N > 3$), Stokes I ($S/N > 3$) and PF ($S/N > 3$) are included.

Our data show an anti-correlation between PF and N_H given by:

$$\log_{10}(PF) = -1.310 \times \log_{10}(N_H) + 31.17 \quad (3.9)$$

with a Pearson correlation coefficient $\rho = -0.56$ for Band 4, and by:

$$\log_{10}(PF) = -1.388 \times \log_{10}(N_H) + 33.146. \quad (3.10)$$

with $\rho = -0.50$ for Band 7. The linear fit was done taking into account the uncertainties in PF using the orthogonal distance regression method. The trends in Figure 3.13 indicate that the observed decrease of PF with N_H in the Planck data continues at even higher column densities. A similar trend has been observed in Galactic cold cores and star-forming regions using JCMT and ALMA data (e.g., Koch et al., 2022; Lin et al., 2024), although it is often reported as a trend between polarisation fraction and total intensity rather than N_H . We note that the values of PF observed in NGC 253 across the column density range $10^{23} < N_H < 4 \times 10^{23} cm^{-2}$ tend to sit slightly higher than the trend line identified by Planck Planck Collaboration et al. (2015a), although both our results and the Planck results show a large scatter. This discrepancy might be due to a more favourable orientation of the magnetic field direction in our observed field-of-view in NGC 253.

3.8.3 PF versus $\mathcal{S}$ relation

Recent polarisation studies also analyse the relation between PF and polarisation angle dispersion function $\mathcal{S}$ (see Section 3.6.3), which quantifies the local order of PA , the magnetic field direction as projected on the sky (Alina et al., 2023; Planck Collaboration et al., 2015a). The all-sky maps of $\mathcal{S}$ constructed from the Planck polarisation data at 350 GHz show intricate filamentary structures of high $\mathcal{S}$ values that share no common structures with column density filaments, except possibly along the Galactic plane. These ridges appear to separate regions with rapidly varying polarisation angles from

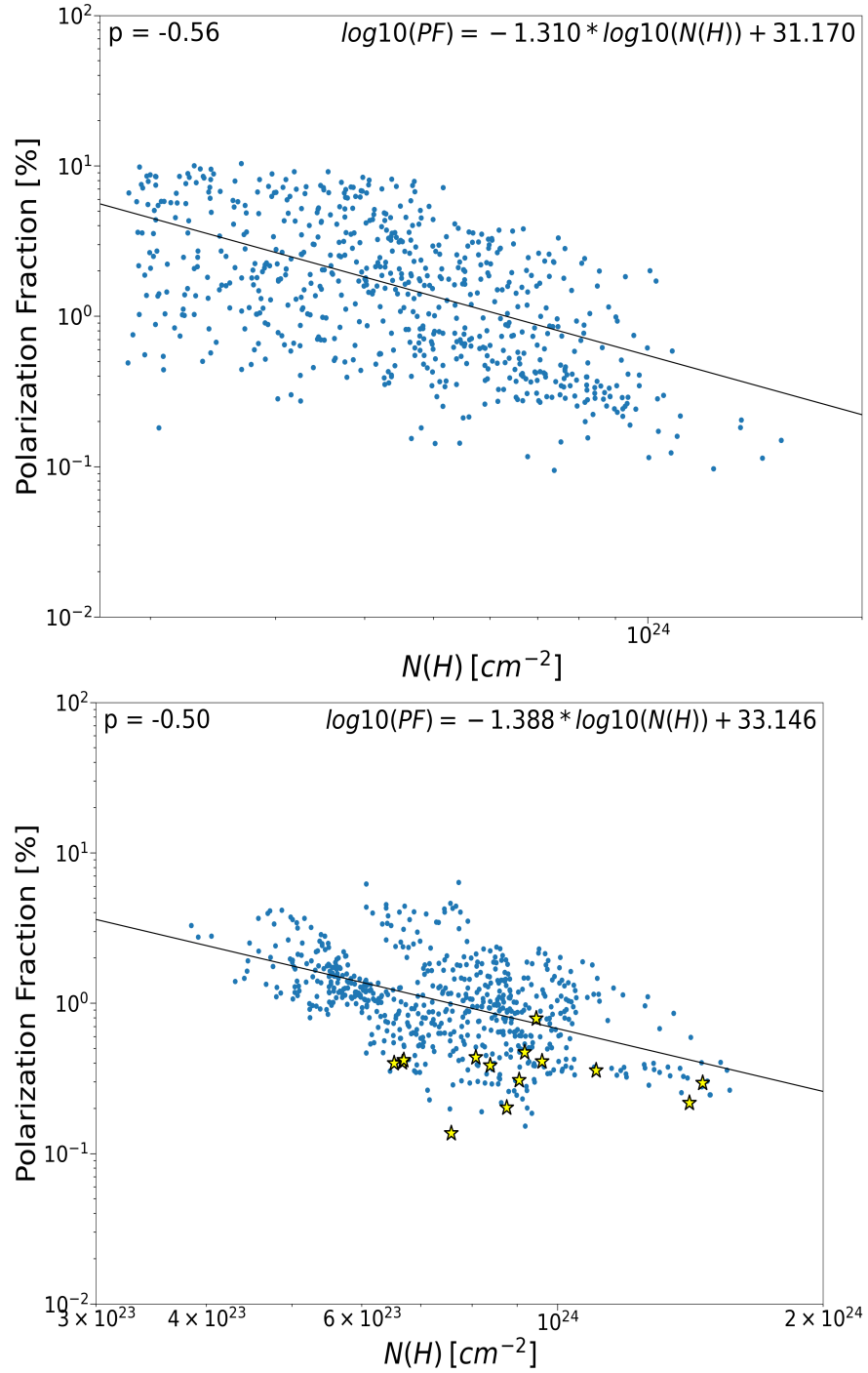


Figure 3.13. Scatter plot of the observed polarisation fraction PF as a function of gas column density in NGC 253. Band 4 data are shown on top panel, Band 7 in the bottom panel. The black line shows the trend derived from a fit to our data (see Equation 3.9 and 3.10). The yellow stars in the bottom panel indicate values computed at the location of the 14 SSCs (see Figure 3.7).

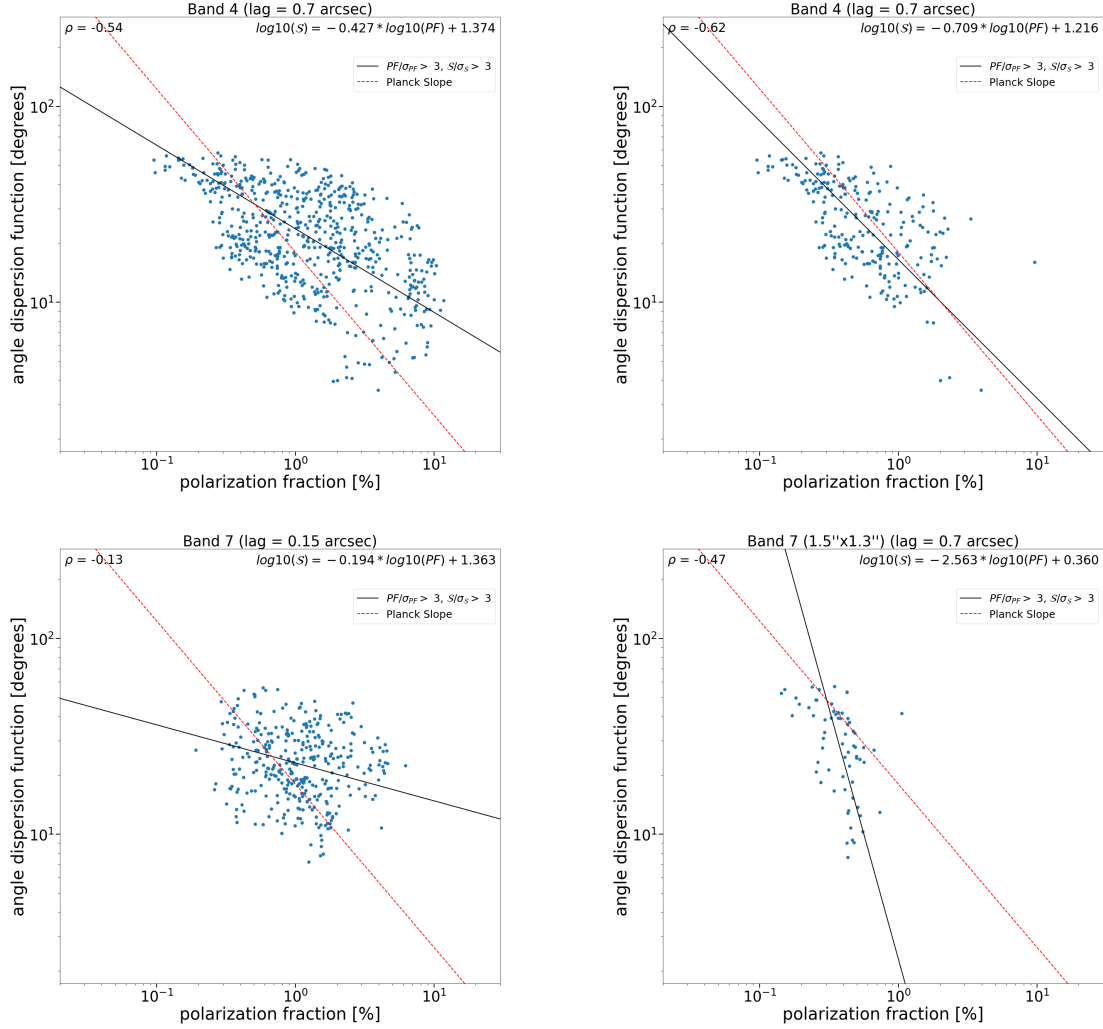


Figure 3.14. Observed polarisation angle dispersion $\mathcal{S}$ as a function of the polarisation fraction PF . Band 4 data are shown on the top left panel, Band 7 on the bottom left. On each plot, the black dashed line shows the trend derived from best fitting the data (see Equation 3.11) excluding all pixels characterised by $I/\sigma_I < 3$, $PF/\sigma_{PF} < 3$ and $\mathcal{S}/\sigma_{\mathcal{S}} < 3$, while the red line shows the best correlation obtained for the solar neighbourhood in the MW from the Planck data for reference. The upper right panel and the lower right panel shows the same plots computed in Band 4 and Band 7 smoothed at the common resolution of $1.5'' \times 1.3''$ using pixels belonging exclusively in the central starburst region, defined by the mask identified in Band 7 (at its native resolution) including pixels with S/N in total intensity larger than 3. On top of each panel the lag used to computed the angle dispersion function $\mathcal{S}$ is indicated.

regions with more coherent PA . The Planck analysis showed a clear anticorrelation between PF and $\mathcal{S}$, indicating that most of the variation in PF in the Planck data is depolarisation due to the tangling of the magnetic field within the beam and/or along the LOS.

In Planck Collaboration et al. (2015b), predictions based on MHD simulations were compared to the data, showing a similar anti-correlation between PF and $\mathcal{S}$, again suggesting that tangling of the field was responsible for the observed variations of PF . The simulations, however, were limited to column density values less than $N_H = 3 \times 10^{22} \text{ cm}^{-2}$, and the Planck data at the resolution used for polarisation analysis did not exceed $N_H = 10^{23} \text{ cm}^{-2}$ where other physical effects could become important. The central starburst region of NGC 253 allows us to explore a higher N_H regime.

The upper and lower left panels of Figure 3.14 show the correlation between PF and $\mathcal{S}$ from our observations in Band 4 and Band 7. Only pixels with $I/\sigma_I > 3$, $PF/\sigma_{PF} > 3$ and $\mathcal{S}/\sigma_{\mathcal{S}} > 3$ are included. Following Planck Collaboration et al. (2015a), we fit a straight line to the data in log-log given by

$$\log(\mathcal{S}) = \alpha \times \log(PF) + \beta, \quad (3.11)$$

which we overlay on Figure 3.14 in black. The linear fit was done taking into account the uncertainties in PF and $\mathcal{S}$ using the orthogonal distance regression method. The correlation derived in the Planck Milky Way (MW) data is also shown on the figure as a red dotted line for reference. We find $\alpha = -0.427$ and $\beta = 1.374$ for Band 4 data and $\alpha = -0.194$ and $\beta = 1.363$ for Band 7 data. The Pearson correlation coefficients are $\rho = -0.54$ and $\rho = -0.13$ for Band 4 and Band 7, respectively, denoting an overall moderate anti-correlation for Band 4 and a little to no anti-correlation for Band 7.

The upper and lower right panels in Figure 3.14 show the correlation between PF and $\mathcal{S}$ for the two Band 4 and Band 7 images convolved to the Band 4 beam ($1.5'' \times 1.3''$) and using a lag of $0.70''$ for the $\mathcal{S}$ computation. In this case, we applied the same mask used in Section 3.6.4, which only includes pixels with $I/\sigma_I > 3$ in Band 7 at native resolution. Additionally, we excluded all pixels with $PF/\sigma_{PF} < 3$ and $\mathcal{S}/\sigma_{\mathcal{S}} < 3$. In this case, the anti-correlation is tight in both bands, with a Pearson index of -0.62 and -0.47 for Band 4 and Band 7, respectively. The anti-correlation observed at these scales at both bands is consistent with the similarities observed in maps of $\mathcal{S}$ and PF , when smoothed to the same angular resolution (see Section 3.7). This indicates that the same magnetic field structure is traced by both dust and synchrotron emission in the central regions of NGC 253 at $\sim 25 \text{ pc}$ scales. Overall, the dependence of PF with $\mathcal{S}$ and N_H is quite similar to what was observed in Planck Collaboration et al. (2015a) in the MW.

In Band 7 at native resolution (lower left panel of Figure 3.14), we see a different behaviour compared to the MW Planck results. At this scale (~ 5 pc), the anticorrelation between N_H and PF is still present, while we see no anticorrelation between $\mathcal{S}$ and PF . This could indicate that thermal dust polarisation varies independently of the apparent magnetic field tangling at column densities larger than $N_H \simeq 10^{23} \text{ cm}^{-2}$ and scales $\lesssim 5$ pc. It might suggest that, at scales of ~ 5 pc in NGC 253, the physical properties of the ISM, rather than the tangling of the magnetic fields, control the observed depolarisation. Although we do not have access to ~ 5 pc in Band 4 data, this divergent behaviour appears to be primarily caused by the different scales that characterise the Band 4 and Band 7 data, rather than the contributions of synchrotron and dust in these bands, since the correlation between PF and $\mathcal{S}$ is recovered in Band 7 when the image is smoothed to the same resolution of Band 4, even though the slope and ρ index are different.

3.9 Conclusions

In this chapter we have presented ALMA Band 4 (145 GHz) and Band 7 (350 GHz) polarisation measurements for the central ~ 200 pc of the starburst galaxy NGC 253. We have derived maps of the polarisation intensity and fraction, of the magnetic field orientation and polarisation angle dispersion function, as well as the corresponding pixel-by-pixel signal-to-noise maps. The reported uncertainties on the polarisation results account for the covariance between the Stokes I, Q, and U parameters. The uncertainties allow us to detect PF as low as 0.1% with a S/N greater than 3. The polarisation properties measured at Bands 4 and 7 exhibit distinct characteristics, reflecting the different emission mechanisms that dominate at each band.

To evaluate the contributions of synchrotron, free-free, and dust in the region, we conducted an SED-fitting analysis using archival data from ALMA and VLA across the frequency range 1 – 350 GHz. At Band 7, the total intensity is mainly thermal dust emission, while Band 4 comprises significant contributions from free-free, dust, and synchrotron emission. By assuming a constant PF for the synchrotron and dust components in the 150–350 GHz range, we estimated the PF values for these components for our observed field and various smaller regions. We find that the synchrotron emission is more polarised than the dust emission in all analysed regions. This higher polarisation fraction of the synchrotron component appears to be the primary reason for the higher than expected polarisation observed in Band 4 maps, despite the significant contribution from (unpolarised) free-free emission at this frequency.

The analysis also revealed a sharp decline in PF estimates for the very centre of

the starburst region (labelled as SC), which is characterised by high column density values and the presence of several super star clusters. This decline is likely caused by different factors, including significant non-polarised radiation from free-free emission and magnetic field fluctuations along the line-of-sight. The more pronounced decrease for the dust polarisation fraction in this central region suggests that differential tangling between the dense and more diffuse medium along the line of sight, and/or a dependence of the grain alignment or destruction of dust particles with environment may also play a role.

Using archival high-resolution ALMA observations of the CO(3-2) line and our debiased polarimetric data, we investigated the correlation between PF and N_H in NGC 253. We found a significant anti-correlation between PF and N_H . This trend suggests that the decrease in PF with N_H observed in Planck data ([Planck Collaboration et al., 2015a](#)) continues to even higher column densities.

Furthermore, the PF and the polarisation angle dispersion function $\mathcal{S}$ are moderately anti-correlated in both bands when smoothed to spatial scales of ~ 25 pc. At its native spatial resolution of ~ 5 pc, we find no relationship between PF and $\mathcal{S}$ in the Band 7 data. Our results suggest that the tangling of the magnetic field is the main cause of the observed depolarisation at scales ~ 25 pc, while other factors play a role at scales ~ 5 pc. Further studies are required to test the effect of environment and spatial scale on the polarised emission of dust grains.

The similarity of the magnetic fields orientation maps for Bands 4 and 7 images convolved at common resolution suggests that, on spatial scales ~ 25 pc, the same magnetic field configuration is traced by both bands. This indicates that while the distinct contributions of synchrotron and dust influence the observed polarisation fraction characteristics, the magnetic field structures are largely unaffected at these scales.

From a qualitative analysis, the magnetic field morphology seems to be coupled with the multi-phase outflow observed in the central region of NGC 253. The magnetic field probed by Band 4 data follows the base of the biconical outflow, mirroring its profile. The conical outflow and the magnetic fields both seem to originate in the central region SC. This region is characterised by the presence of several super starclusters with exceptionally high broad linewidth $H40\alpha$ emission, which may be the main responsible in driving the ionised component of the multi-phase outflow. The high polarisation fraction of the synchrotron component estimated at the launch site of the outflow could be explained if the magnetic fields are compressed and ordered by the strong winds produced by the SSCs. A coupling between the magnetic field and the molecular outflow is seen mostly along the direction of the SW streamer, where the magnetic field probed

by Band 4 data seems to be disrupted on the northern sides of the midplane. Overall, our results highlight the interplay between magnetic fields, star formation, and outflows in shaping the central region of NGC 253.

Appendix A3: Calibration validation

In this Appendix we present the diagnostic plots used to validate the quality of the polarisation calibration in both the visibility and image domains.

As a first validation step, we analyse the cross-hand visibilities (XY and YX) of the polarisation calibrator J0006–0623. For both Band 4 and Band 7, we examine the cross-hand amplitude and phase as a function of frequency for a representative baseline after the full polarisation calibration (Figures 3.15 and 3.17). To improve clarity and reduce noise, these quantities are averaged over all time samples and over groups of eight frequency channels. We also inspect their distribution in the complex plane (real versus imaginary part; Figures 3.16 and 3.18), where the visibilities are averaged over time, all frequency channels, and all baselines to enhance the signal-to-noise ratio and highlight the global behaviour of the correlations. These diagnostics are commonly used to verify the absence of residual instrumental polarisation and to assess the stability of the calibration across the observed bandwidth.

In both bands, the amplitudes remain stable across the full bandwidth, showing no systematic frequency dependence, while the phases are smooth and free of abrupt jumps. The XY and YX correlations exhibit consistent behaviour, and the comparison of the complex-plane distributions before and after calibration reveals a clear improvement: the initially scattered points become tightly clustered after calibration. This behaviour indicates the effective removal of instrumental polarisation leakage and the absence of significant residual calibration artefacts.

As a second validation, we inspect the Stokes I, Q, U and V images of the polarisation calibrator J0006–0623 after the full calibration, in both Band 4 and Band 7 (Figures 3.19 and 3.20). These images are used to verify the absence of residual instrumental artefacts in the image domain.

The total intensity emission is compact and centred at the expected calibrator position, as expected for unresolved sources. The Stokes Q and U maps show the expected polarised signal for the polarisation calibrator. The Stokes V emission is consistent with zero within the noise level. This behaviour is expected, since circular polarisation was assumed to be negligible during the polarisation calibration procedure (see Section 3.3).

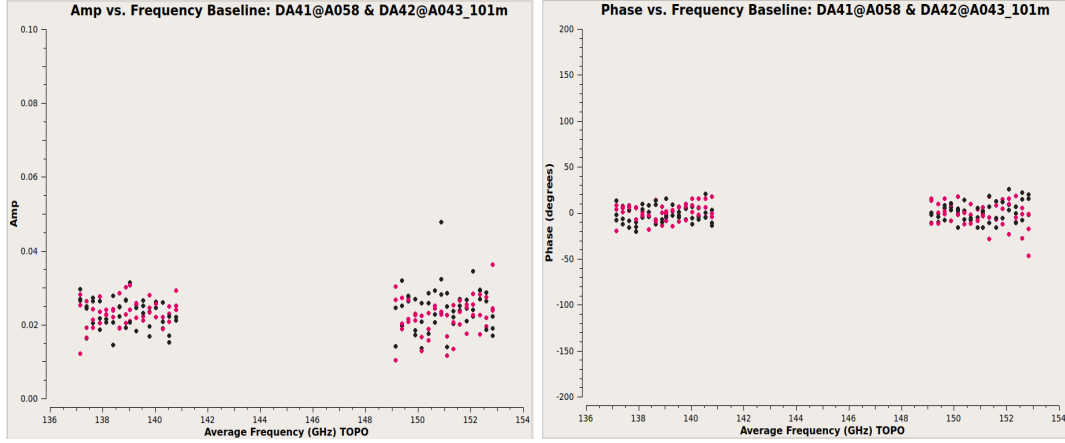


Figure 3.15. Cross-hand (XY and YX) visibility amplitude (left panel) and phase (right panel) as a function of frequency for the polarisation calibrator J0006–0623 in Band 4, shown for a representative baseline after the full polarisation calibration. The data were averaged over 8 spectral channels and over all available time samples in order to improve the signal-to-noise ratio.

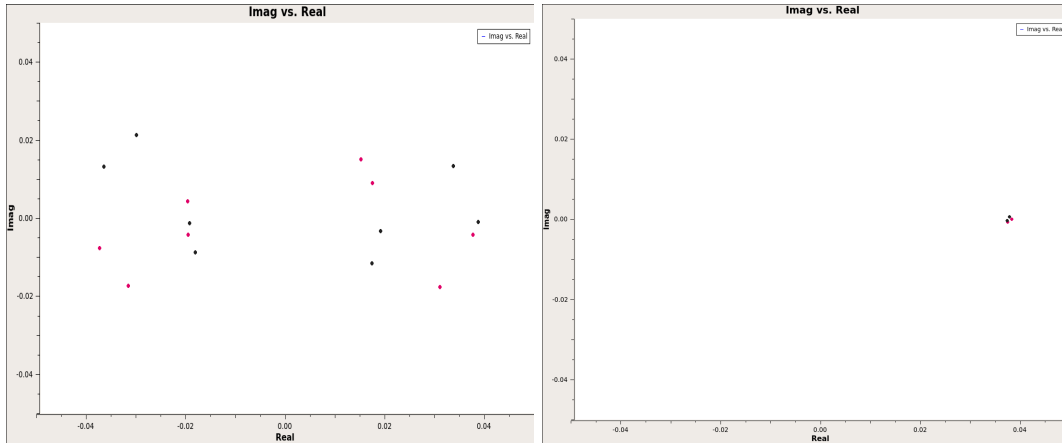


Figure 3.16. Distribution of the cross-hand visibilities (XY and YX) in the complex plane for the polarisation calibrator J0006–0623 in Band 4. The visibilities are averaged over time, frequency channels, and baselines in order to increase the signal-to-noise ratio. Left panel: data before the full polarisation calibration. Right panel: data after the full polarisation calibration.

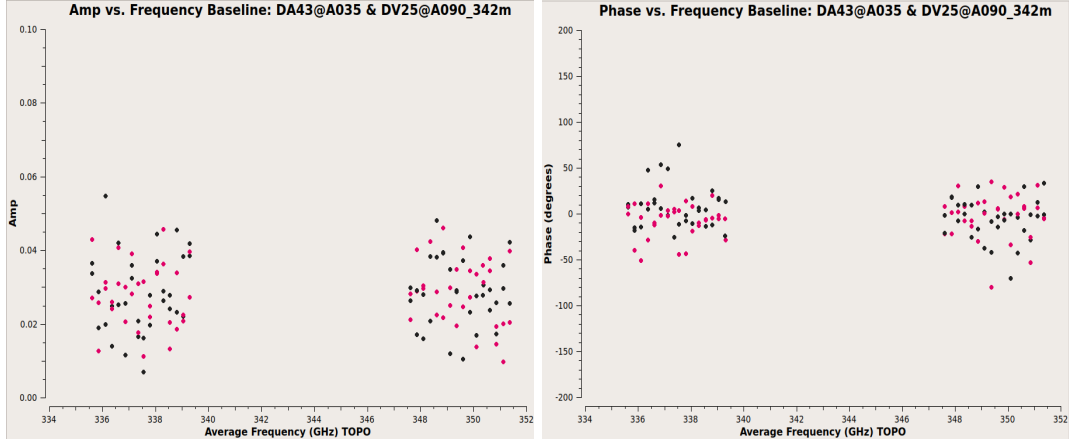


Figure 3.17. Cross-hand (XY and YX) visibility amplitude (left panel) and phase (right panel) as a function of frequency for the polarisation calibrator J0006–0623 in Band 7, shown for a representative baseline after the full polarisation calibration. The data were averaged over 8 spectral channels and over all available time samples in order to improve the signal-to-noise ratio.

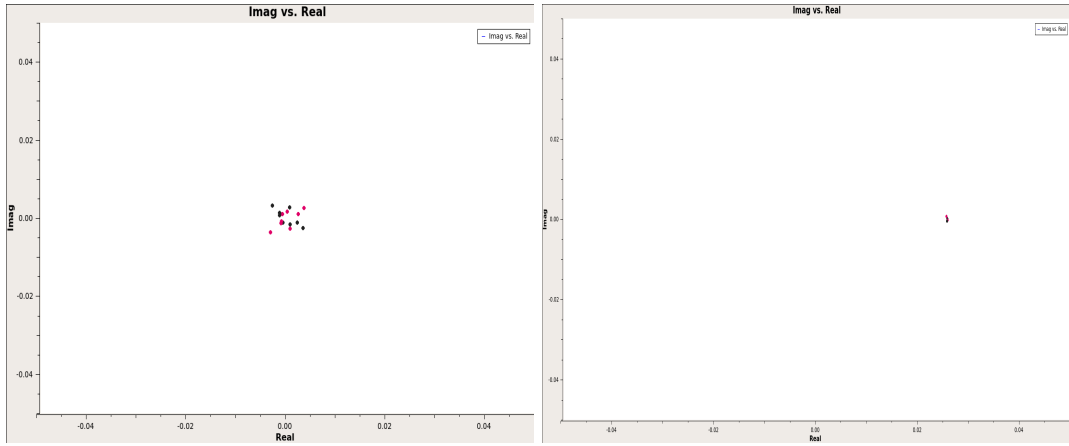


Figure 3.18. Distribution of the cross-hand visibilities (XY and YX) in the complex plane for the polarisation calibrator J0006–0623 in Band 7. The visibilities are averaged over time, frequency channels, and baselines in order to increase the signal-to-noise ratio. Left panel: data before the full polarisation calibration. Right panel: data after the full polarisation calibration.

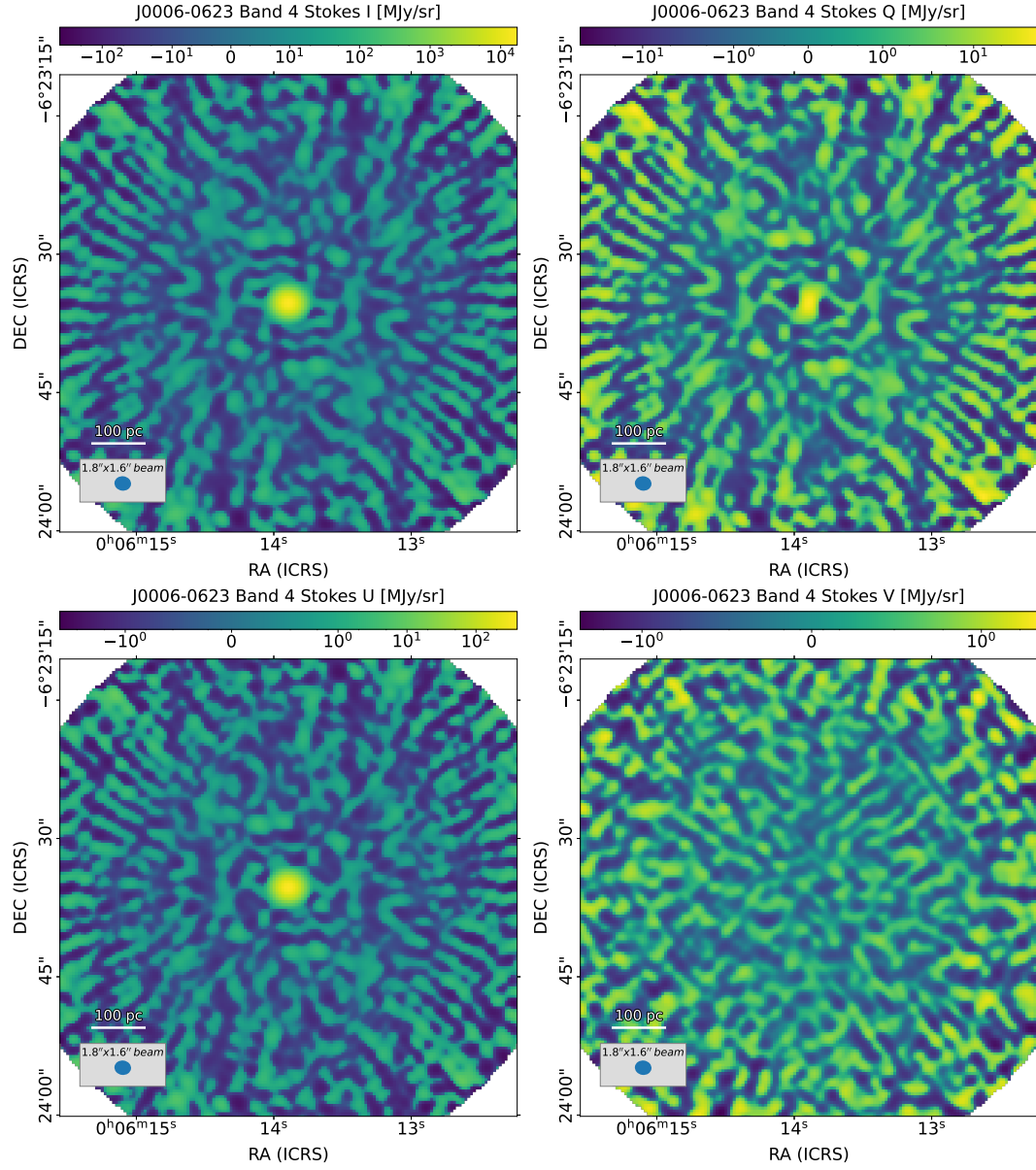


Figure 3.19. Stokes I, Q, U and V images of the polarisation calibrator J0006-0623 in Band 4 after the full polarisation calibration. The source is compact in total intensity and no spurious large-scale or directional patterns are visible in the polarisation images.

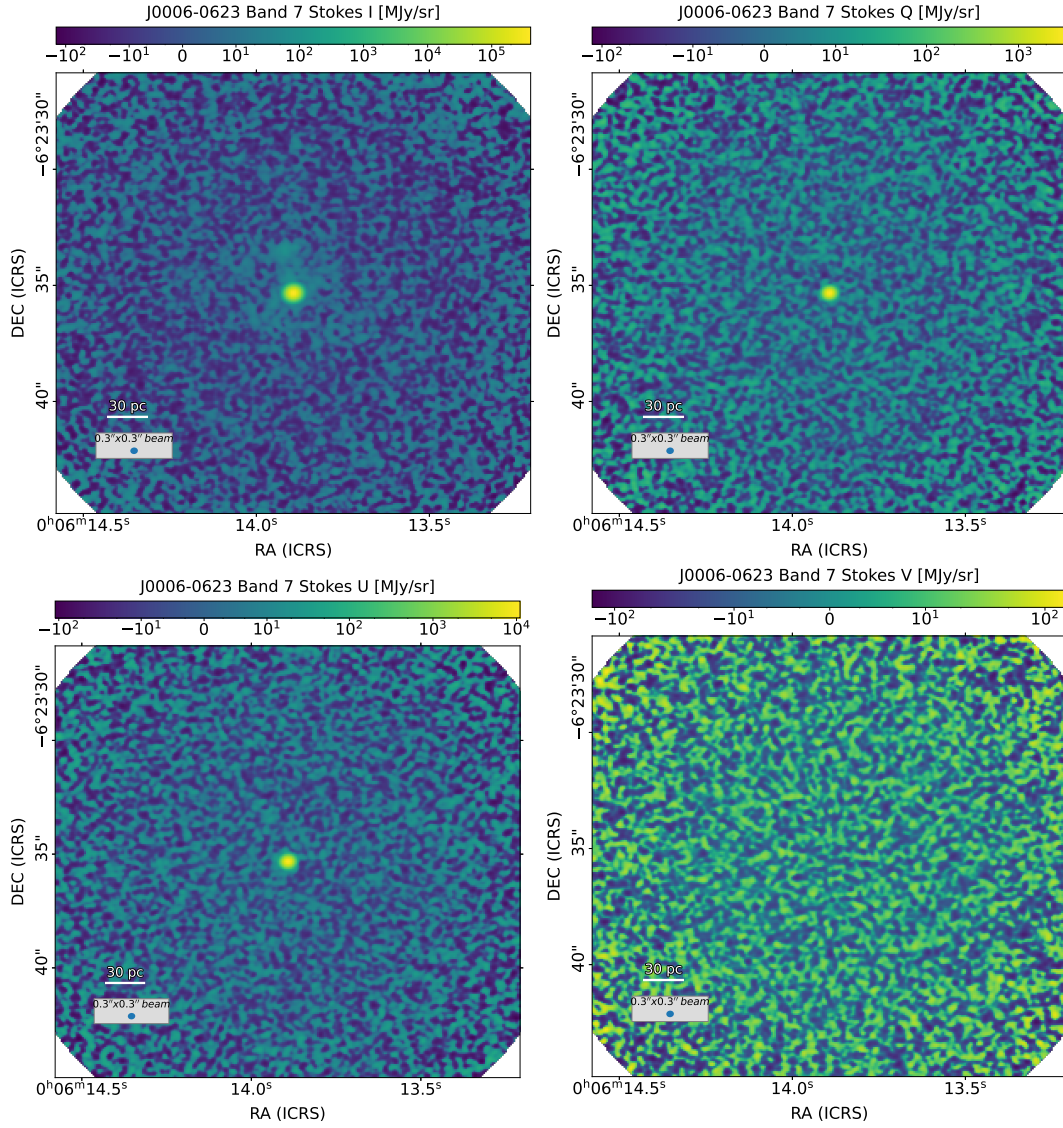


Figure 3.20. Same as Fig. 3.19, but for Band 7.

Appendix B3: Robustness of the polarisation angle dispersion function to the choice of lag

To assess the robustness of the polarisation angle dispersion function to the adopted lag, we recomputed the $\mathcal{S}$ maps for a set of lags centred on the fiducial value used in the main text. For each pixel, $\mathcal{S}(\mathbf{x}, l)$ is defined as the standard deviation of the polarisation angles of neighbouring pixels lying in the annulus

$$l \leq r \leq l + \delta l,$$

with annulus width set to $\delta l = l$.

For each band, the explored lag values are chosen as fixed fractions of the synthesised beam major axis, θ_{maj} . Specifically, we consider three representative spatial scales corresponding to $0.5 \theta_{\text{maj}}$ (fiducial), $0.75 \theta_{\text{maj}}$, and $1.0 \theta_{\text{maj}}$. This choice ensures that the dispersion function is evaluated on physically resolved scales directly tied to the angular resolution of each dataset.

For Band 7 ($\theta_{\text{maj}} = 0.30''$), the adopted lags are $l = 0.15''$, $0.225''$, and $0.30''$. The corresponding maps are shown in Figure 3.21. Only pixels satisfying $I/\sigma_I > 3$ and $S/\sigma_S > 3$ are displayed, as indicated in the figure labels. Magnetic-field orientation vectors are overplotted where $S/\sigma_S > 3$. As expected for a scale-dependent statistic, increasing the lag progressively smooths the small-scale texture of $\mathcal{S}$, and the high-dispersion filamentary structures appear broader and more continuous. However, the overall morphology — in particular the prominent high-dispersion filament and the boundaries between regions of coherent polarisation orientation — remains clearly preserved across all tested values. The pixel-by-pixel distributions (Figure 3.22) show substantial overlap and similar widths, with a systematic shift of the median from $\sim 38^\circ$ at the smallest lag to $\sim 45^\circ$ at the largest lag. This modest increase does not modify the qualitative interpretation, indicating that the dispersion properties in Band 7 are primarily driven by the intrinsic spatial structure of the polarisation angle field rather than by the specific choice of lag.

The same analysis is performed for Band 4 ($\theta_{\text{maj}} = 1.4''$), adopting $l = 0.70''$, $1.05''$, and $1.40''$. The corresponding maps (Figure 3.23) exhibit the same general behaviour: larger lags produce smoother structures and a more continuous high-dispersion ridge, while the global morphological features remain unchanged. The pixel distributions (Figure 3.24) again largely overlap, with a systematic shift of the peak and median towards higher $\mathcal{S}$ values as the lag increases. Owing to the coarser angular resolution of Band 4, the dispersion function already traces predominantly large-scale variations

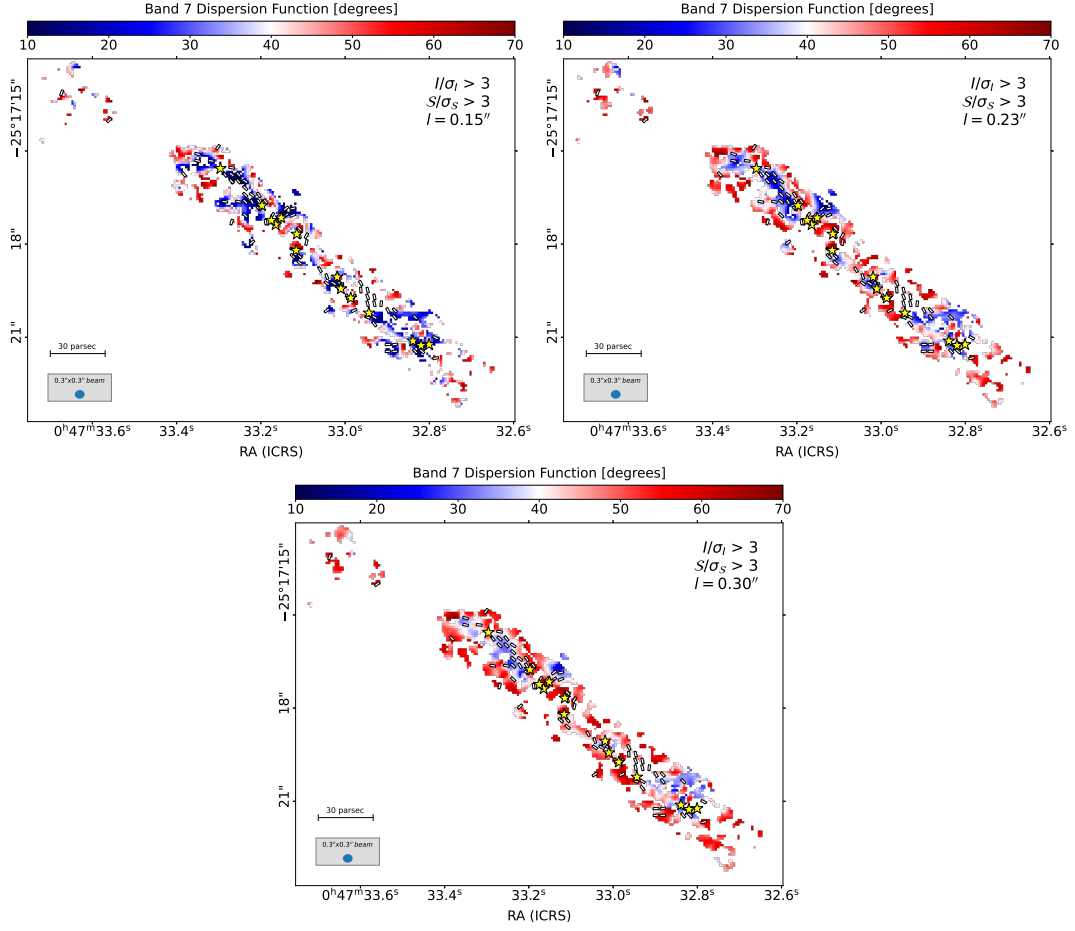


Figure 3.21. Polarisation angle dispersion function maps for Band 7 at three different lags. From left to right: $l = 0.15''$, $0.225''$, $0.30''$. Only pixels with $I/\sigma_I > 3$ and $S/\sigma_S > 3$ are shown. Magnetic-field vectors are overlaid where $S/\sigma_S > 3$. Yellow stars mark the positions of super star clusters from [Leroy et al. \(2018\)](#).

of the polarisation angle field; increasing the lag further mainly suppresses residual small-scale fluctuations without altering the overall physical picture.

Overall, these tests demonstrate that the main morphological features and statistical properties of the polarisation angle dispersion function are robust against reasonable variations of the lag parameter within one beam.

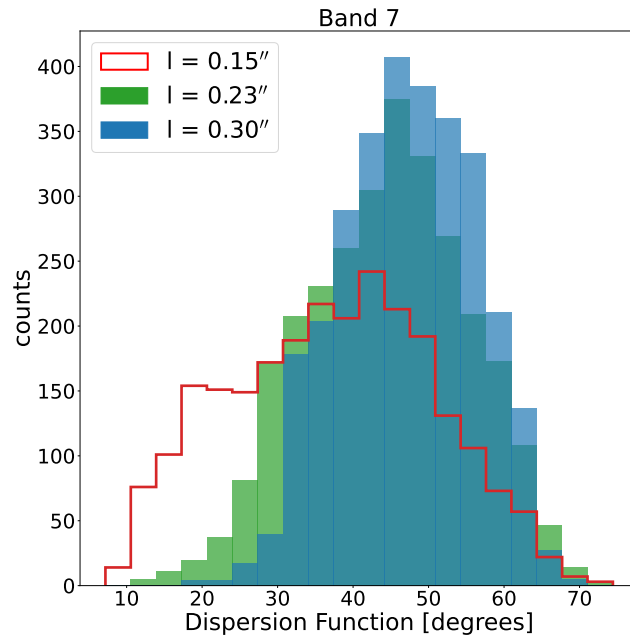


Figure 3.22. Pixel-by-pixel distributions of the Band 7 polarisation angle dispersion function for the three lag values.

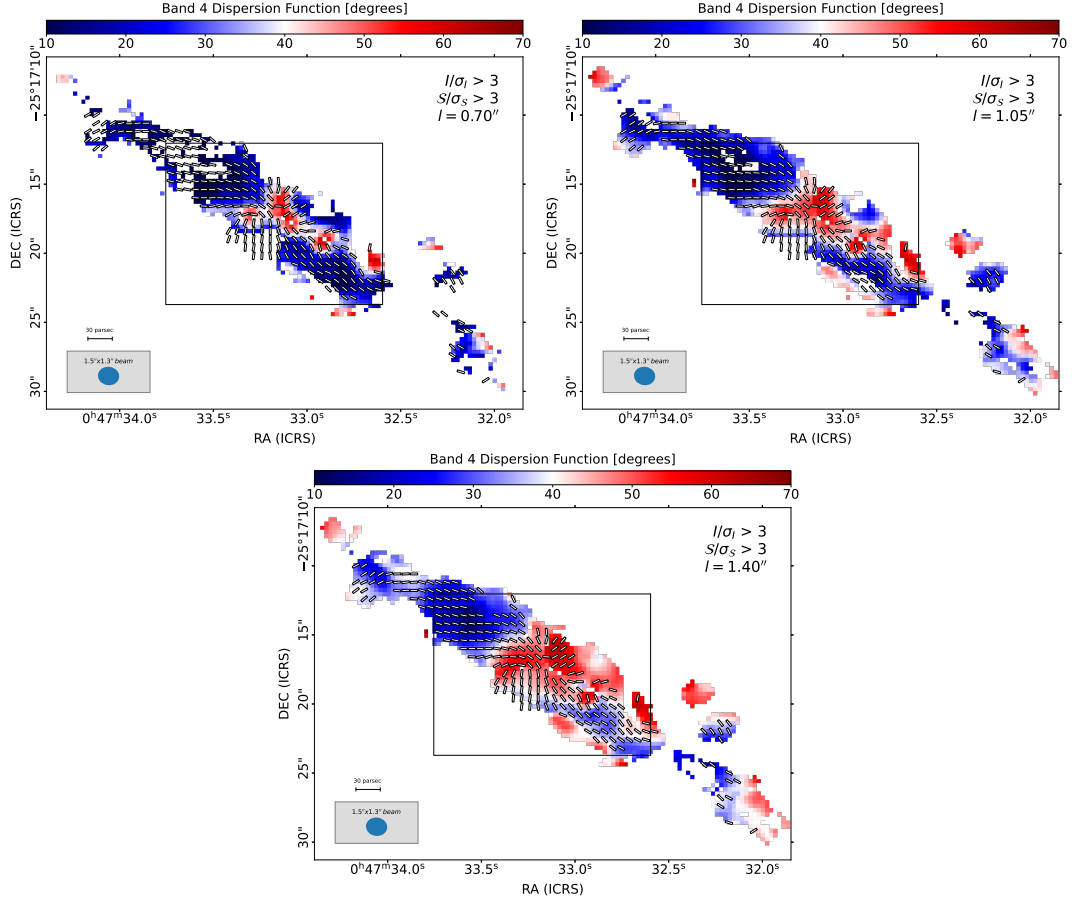


Figure 3.23. Polarisation angle dispersion function maps for Band 4 at three different lags. From left to right: $l = 0.70''$, $1.05''$, $1.40''$. Only pixels with $I/\sigma_I > 3$ and $S/\sigma_S > 3$ are shown. Magnetic-field vectors are overlaid where $S/\sigma_S > 3$.

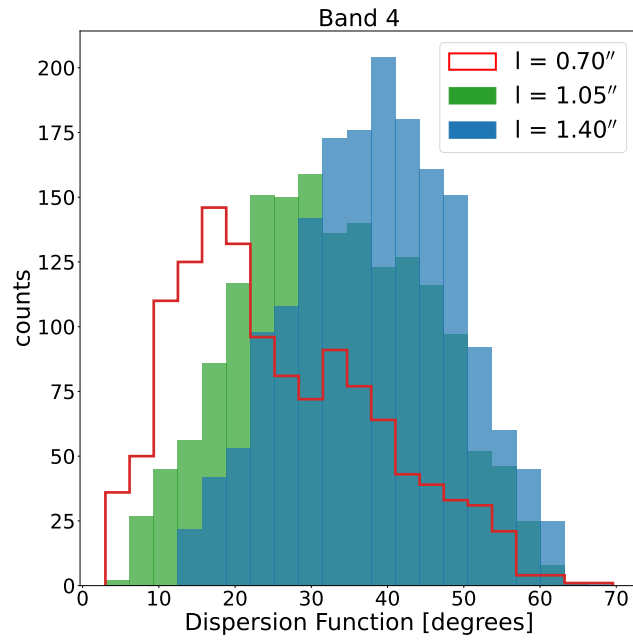


Figure 3.24. Pixel-by-pixel distributions of the Band 4 polarisation angle dispersion function for the three lag values.

II

MHD Simulations and Synthetic Diagnostics

4

Magnetohydrodynamic Simulations of Galaxy Formation

Modern astronomical surveys provide increasingly detailed observations of galaxies across cosmic time, revealing their stellar, gaseous, and magnetic properties with remarkable precision. However, observations alone provide only static snapshots of a galaxy’s evolution. To uncover the physical mechanisms that drive these processes—such as star formation, feedback, and magnetic-field amplification—one must complement observations with theoretical models capable of following their dynamical evolution.

Cosmological magnetohydrodynamical (MHD) simulations offer this complementary approach. By evolving gravity, gas dynamics, magnetic fields, radiation, and cosmic rays within a self-consistent cosmological framework, they enable us to study processes that are often inaccessible to direct observation, including how magnetic fields originate, amplify, and interact with the multiphase interstellar medium.

This chapter introduces the MHD framework and numerical methods that underpin the simulations used in this thesis. The first three sections focus on the general aspects of MHD galaxy formation. Section 4.1 discusses the importance of including magnetic fields in galaxy evolution models and their impact on the interstellar and circumgalactic media. Section 4.2 outlines the cosmological framework in which these simulations are embedded, describing the Λ CDM background and the treatment of dark matter and baryons. Section 4.3 presents the governing MHD equations and the numerical techniques used to solve them, including field seeding, amplification, and adaptive mesh refinement. Finally, Section 4.4 focuses specifically on the AZAHAR cosmological zoom-in simulations employed in this work, detailing their physical modules, numerical setup, and implementation of the RTnsCRiMHD configuration.

4.1 Why include MHD?

Magnetic fields are energetically subdominant in cosmological context, but in the interstellar and circumgalactic media (ISM/CGM) they can approach equipartition with thermal and turbulent pressures (see Section 1.5). As a result, they (i) provide pressure and tension support, (ii) regulate cloud formation and star-formation efficiencies, (iii)

influence angular-momentum transport, and (iv) shape, collimate, and load galactic outflows. Historically, large cosmological runs often omitted MHD because field amplification proceeds via small-scale dynamos (see Section 1.3) that are only marginally resolved, and because maintaining numerically stable magnetic fields is computationally challenging. These limits are now routinely overcome in state-of-the-art codes (Teyssier, 2002; Fromang et al., 2006; Pakmor & Springel, 2013). To study magnetic field effects in a realistic Universe, we place MHD simulations within a standard cosmological framework, described next.

4.2 Cosmological Context

All simulations adopt the standard cosmological model, known as flat Λ CDM, which assumes a Universe with zero curvature, dominated by dark energy (Λ) and cold dark matter (CDM). This model is consistent with observations of the Universe's large-scale structure (e.g., Planck Collaboration et al., 2020). The simulations begin with initial conditions that describe small density fluctuations in the early Universe, modelled as a Gaussian random field to match statistical properties observed in the cosmic microwave background and galaxy distributions. These fluctuations are set up in either periodic volumes (representing a large, repeating box of the Universe) or "zoom-in" regions (focusing on a specific area, like a galaxy, with higher resolution).

The simulations discretize the Universe using resolution elements, which represent either particles (in Lagrangian methods) or grid cells (in Eulerian methods). In particle-based approaches, each particle carries a fixed mass and follows the modeled physical laws (such as gravity and gas dynamics), with properties like density and velocity smoothed over neighboring particles. In grid-based approaches, the simulation volume is divided into discrete cells on a mesh, where fluid quantities are evolved according to physical equations, allowing for adaptive refinement to capture fine-scale structures (Vogelsberger et al., 2020).

Initial conditions are generated with Lagrangian perturbation theory (LPT), which yields a displacement and velocity field for matter. Particles sample this field and are displaced accordingly; on Eulerian meshes the grid is not moved, instead the gas density and velocity fields are initialized by interpolating the same LPT solution onto the mesh (Zel'dovich, 1970; Bouchet et al., 1995; Crocce et al., 2006).

Dark matter is modeled using an N -body method, where dark matter is represented as particles that interact only through gravity. The gravitational forces are calculated on the same adaptive mesh used for the gas dynamics (described in Section 4.3),

ensuring consistency between the gas and dark matter components. This mesh-based gravity solver computes the gravitational potential ϕ by solving the Poisson equation in comoving coordinates,

$$\nabla_x^2 \phi = 4\pi G a^2 (\rho_{\text{DM}} + \rho_{\text{baryonic}} - \bar{\rho}), \quad (4.1)$$

where a is the cosmological scale factor, G is the gravitational constant, and $\bar{\rho}$ is the mean matter density of the Universe. Here $\rho_{\text{baryonic}} = \rho_{\text{gas}} + \rho_{\star}$ includes both gas and stellar components (Vogelsberger et al., 2020).

4.3 Numerical Methods

Magnetohydrodynamics Equations. MHD is a framework used to study how electrically conducting fluids, like plasmas or ionized gases, interact with magnetic fields. In astrophysics, it is often applied to understand phenomena in stars, galaxies, or interstellar gas. In the ideal MHD approximation, the plasma is assumed to have negligible electrical resistivity, so that magnetic field lines are perfectly "frozen" into the fluid and move with it. The evolution of the gas and magnetic fields is then governed by the following set of equations:

(1) Mass Conservation

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (4.2a)$$

This equation ensures that the total mass of the gas (represented by the density, ρ) does not just appear or disappear—it can only move with the gas's velocity ($\mathbf{v}$).

(2) Momentum Evolution

$$\partial_t(\rho \mathbf{v}) + \nabla \cdot \left[\rho \mathbf{v} \mathbf{v} + \left(P + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{\mathbf{B} \mathbf{B}}{4\pi} \right] = -\rho \nabla \Phi, \quad (4.2b)$$

This equation describes how the gas momentum density, $\rho \mathbf{v}$, evolves in time. The first term, $\nabla \cdot (\rho \mathbf{v} \mathbf{v})$, represents the transport (or flux) of momentum by the moving fluid. The quantity $\mathbf{v} \mathbf{v}$ is a dyadic product, whose components are $(v_i v_j)$, and $\mathbf{I}$ is the identity tensor ($\mathbf{I}_{ij} = \delta_{ij}$). The term $P \mathbf{I}$ corresponds to the isotropic gas pressure, while $(B^2/8\pi) \mathbf{I}$ represents the magnetic pressure exerted by the magnetic field $\mathbf{B}$. The final magnetic term, $-\mathbf{B} \mathbf{B}/4\pi$, introduces anisotropic magnetic tension, which acts along the field lines and tends to straighten them. On the right-hand side, $-\rho \nabla \Phi$ accounts for the gravitational force.

(3) Energy Evolution

$$\partial_t U_{tot} + \nabla \cdot \left[\left(U_{tot} + P + \frac{B^2}{8\pi} \right) \mathbf{v} - \frac{(\mathbf{B} \cdot \mathbf{v}) \mathbf{B}}{4\pi} \right] = -\rho \mathbf{v} \cdot \nabla \Phi, \quad (4.2c)$$

This equation describes changes in the total energy U_{tot} , which includes the gas’s kinetic energy (from motion), internal energy (like heat), and magnetic energy. It shows how energy flows with the gas and how it is influenced by magnetic fields and gravity.

(4) Magnetic Field Evolution

$$\partial_t \mathbf{B} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0, \quad \nabla \cdot \mathbf{B} = 0, \quad (4.2d)$$

This equation governs how the magnetic field changes. It moves with the gas (via the term $\mathbf{v} \times \mathbf{B}$) and must satisfy the constraint $\nabla \cdot \mathbf{B} = 0$, meaning magnetic field lines cannot have loose ends—there are no magnetic monopoles.

Seeding and amplification. In ideal MHD, a strictly zero field remains zero ($\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B})$ implies $\mathbf{B} \equiv 0$ is a solution), so simulations must supply a nonzero seed. Common strategies include: (i) a weak uniform cosmological seed; (ii) explicit source terms that mimic microphysical batteries (e.g. the Biermann battery); and (iii) *astrophysical seeding*, where feedback processes inject magnetized plasma—most often divergence-free loops at supernova events, and sometimes magnetized jets/winds from AGN. These weak seeds are then amplified by small-scale turbulent dynamos and organized by shear/rotation and outflows; in dense ISM phases the field can approach near-equipartition with turbulent/thermal pressures (Kulsrud & Zweibel, 2008; Brandenburg & Subramanian, 2005; Beck, 2015).

Hydrodynamics and Grids. From the computational point of view, to implement MHD the simulation volume is divided into a grid of cells, where each cell represents a small region of space. The state of the fluid (its density ρ , velocity $\mathbf{v}$, pressure P , and magnetic field $\mathbf{B}$) is tracked in each cell over time. These quantities evolve according to the MHD equations.

Instead of using a uniform grid with the same cell size everywhere, which would be computationally expensive for large cosmological volumes, a widely used approach is the so called adaptive mesh refinement (AMR). AMR starts with a coarse grid and refines it by splitting cells into smaller ones only where high resolution is needed—such as regions with dense gas, sharp gradients (e.g., shocks), or strong energy losses (e.g., due

to cooling). In an octree-based AMR a cell is divided into eight smaller cells (halving the size along each axis, reducing the volume by a factor of eight). This allows simulations to achieve fine resolution (e.g., parsec-scale cells in galaxy centers) while keeping larger, less dynamic regions (e.g., intergalactic space) on a coarser grid, making simulations of entire galaxies or cosmological volumes computationally feasible. To ensure that physical quantities like mass, momentum, energy, and magnetic flux are conserved across the grid, especially at boundaries between coarse and fine cells, a process called refluxing is used. Refluxing adjusts the fluxes (the flow of these quantities between cells) at coarse-fine interfaces to prevent inconsistencies, ensuring the simulation remains physically accurate (Berger & Colella, 1989; Teyssier, 2002).

Divergence Control. In MHD simulations, Maxwell’s equations 4.2 require that the magnetic field ($\mathbf{B}$) has no divergence, meaning $\nabla \cdot \mathbf{B} = 0$. This condition ensures that magnetic field lines form closed loops, with no sources or sinks (like magnetic monopoles). To enforce this in numerical simulations, a method called constrained transport (CT) is used (Evans & Hawley, 1988; Fromang et al., 2006). In CT, magnetic field components are stored at the interfaces (faces) of each grid cell, rather than at cell centers, and electric fields are defined at cell edges. The evolution of the magnetic field is computed using Faraday’s law,

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad (4.3)$$

where $\mathbf{E}$ is the electric field. By carefully discretizing this equation, CT ensures that the net magnetic flux through a cell’s face remains zero at each time step, preserving $\nabla \cdot \mathbf{B} = 0$ to machine precision. In simple terms, CT updates the magnetic field in a way that guarantees the total magnetic flux entering and leaving each cell cancels out, maintaining the physical consistency of the magnetic field.

4.4 The Azahar model used in this thesis

In this thesis we use the AZAHAR cosmological zoom-in simulations in the specific configuration RTnsCRiMHD, incorporating the non-thermal physical processes of MHD, radiative transfer (RT), and cosmic rays (CRs). The configuration is described in detail by Martin-Alvarez et al. (2025). The global setup and the nested-resolution strategy are illustrated in Figure 4.1.

The AZAHAR simulations are generated with a customized version of the publicly available RAMSES code (Teyssier, 2002). This code solves for the coupled evolution

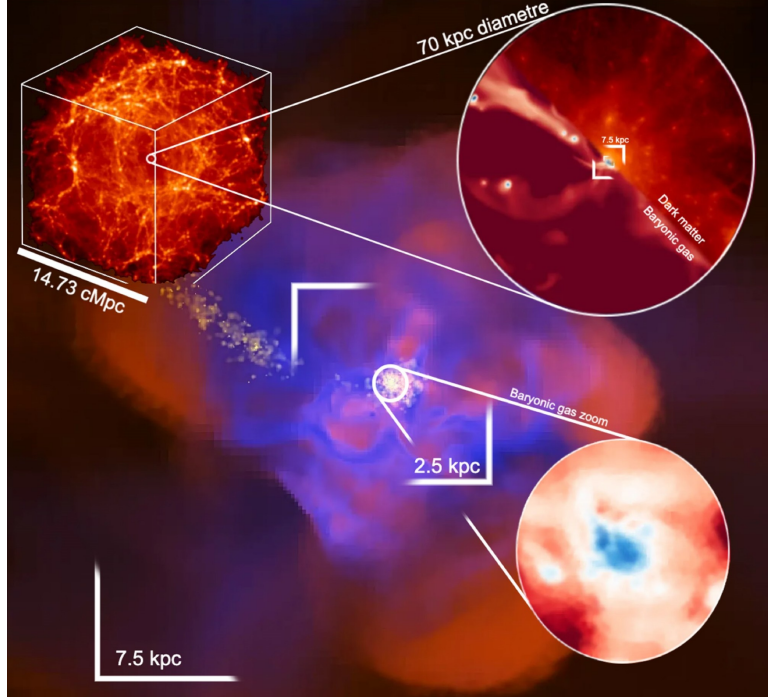


Figure 4.1. Visualization of the AZAHAR cosmological MHD zoom-in setup (RTNSCRIMHD configuration). The large cube shows the full 14.7 cMpc comoving simulation box, highlighting the high-resolution convex hull that encloses the target galaxy. The top-right inset zooms on a 70 kpc region, approximately twice the virial radius, showing the spatial distribution of dark matter (red) and baryonic gas (blue). The main central panel displays the baryonic gas in a 7.5 kpc region around the forming galaxy. The bottom-right zoom shows the baryonic gas morphology in the central 2.5 kpc, where dense star-forming gas dominates the galactic disk. Adapted from [Martin-Alvarez et al. \(2023\)](#).

of baryons and dark matter using an Eulerian grid-based approach for the gas, and a collisionless particle-based scheme for stars and dark matter. These components are coupled through a gravitational potential solved on the mesh. The RAMSES code employs an octree structure Eulerian grid to resolve the magneto-hydrodynamical evolution of the gas component, incorporating an adaptive AMR scheme to increase the resolution in regions of interest. The simulations feature an extensive convex hull zoom region of approximately 10 comoving Mpc. This region allows the AMR scheme to refine down to a minimum cell-size spatial resolution of 20 pc, and has particle mass resolutions of $m_{\text{DM}} \sim 4 \times 10^5 M_{\odot}$ and $m_{*} \sim 4 \times 10^4 M_{\odot}$ for dark matter and stellar components, respectively.

We solve the evolution of magnetic fields through a constrained transport method

(Teyssier et al., 2006; Fromang et al., 2006), which ensures the solenoidal condition ($\nabla \cdot \mathbf{B} = 0$) to machine precision. We assume ideal MHD, with the magnetic field initialized to a uniform Biermann battery-like kinematic seed strength $B \sim 10^{-20}$ G (Martin-Alvarez et al., 2018). In addition to this primordial seed, supernova (SN) feedback further amplifies the field by injecting small-scale magnetic loops (Martin-Alvarez et al., 2021), providing a sustained source of magnetisation.

Radiative transfer uses the implementation by Rosdahl et al. (2013), with a configuration resembling that of the SPHINX simulations (Rosdahl et al., 2018, 2022), modelling three frequency bins corresponding to the ionization of H I ($13.6 \text{ eV} \lesssim \epsilon_{\text{photon}} \lesssim 24.59 \text{ eV}$), He I ($24.59 \text{ eV} \lesssim \epsilon_{\text{photon}} \lesssim 54.42 \text{ eV}$), and He II ($54.42 \text{ eV} \lesssim \epsilon_{\text{photon}}$). The zoom sub-volume reionization is primarily driven by self-consistent star formation, and incorporates a background model by Haardt & Madau (1996).

We employ the cosmic rays solver implementation by Dubois & Commercon (2016) with the improvements by Dubois et al. (2019), but note that the RTnsCRiMHD model has the anisotropic CR streaming deactivated (nsCR). The CR solver accounts hadronic and Coulomb cosmic ray cooling, and anisotropic diffusion with a constant diffusion coefficient $\kappa_{\parallel} = 3 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (Ackermann et al., 2012; Cummings et al., 2016; Pfrommer et al., 2017).

The model incorporates gas cooling above and below 10^4 K through interpolated CLOUDY tables (Ferland et al., 1998) and following Rosen & Bregman (1995), respectively. The RTnsCRiMHD configuration does not explicitly follow a chemical network for H_2 formation and does not evolve a separate molecular-gas component. Star formation is therefore not tied to an H_2 fraction, but is regulated by a sub-grid prescription. Specifically, star formation is modelled via a magneto-thermo-turbulent scheme (Kimm et al., 2017; Martin-Alvarez et al., 2020), enabled at the highest level of refinement when the gravitational pull overcomes local turbulent, thermal, and magnetic support. The star formation rate follows a Schmidt law (Schmidt, 1959; Krumholz et al., 2012), $\dot{\rho}_{\star} = f_{\text{ff}} \rho_{\text{gas}} / t_{\text{ff}}$, where ρ_{gas} is the gas density and f_{ff} is the local efficiency derived from turbulent models (Federrath & Klessen, 2012).

Supernova feedback is implemented through mechanical injection (Kimm & Cen, 2014), where star particles deposit mass, momentum, and energy. Each SN assumes a Kroupa initial mass function (IMF) (Kroupa, 2001), releasing a total energy of $\sim 10^{51}$ erg per $10 M_{\odot}$, returning $\eta_{\text{SN}} = 0.213$ of the mass to the ISM, with $\eta_{\text{metals}} = 0.075$ as metals. SNe inject magnetic energy through local small-scale loops (Martin-Alvarez et al., 2021), with an injection energy of $0.01 E_{\text{SN}}$ per event, leading to magnetisations comparable to SN remnants (Parizot et al., 2006), and consistent with values used by

other authors (Beck et al., 2013; Butsky et al., 2017; Vazza et al., 2017). SN are the exclusive source of CR energy, injecting 10% of the SN energy (Morlino & Caprioli, 2012; Helder et al., 2013). The RTnsCRiMHD model of the AZAHAR simulations has already been described and studied by Witten et al. (2024), Dome et al. (2025) and Yuan et al. (2025), and will be introduced in further detail in Martin-Alvarez et al. (in prep.).

In addition to AZAHAR, we complement our analysis with a Milky Way–like NUT zoom-in galaxy to probe seed-field and SN-injection dependencies; the NUT set-up will be summarised in Chapter 5 (Section 5.1.2).

5

Analysis of Azahar Simulated Galaxies and Comparison with Observations

In this chapter we use the AZAHAR cosmological MHD framework to quantify how magnetic fields grow and become dynamically relevant across galaxy disks, and how this connects to star formation activity and gas content. We focus on theory–observable links such as the relation between the magnetic field strength B and star formation (see Section 1.4), and on energy-budget diagnostics (e.g. the balance among magnetic, turbulent, thermal, and CR components). The analysis is phase-resolved, with results reported separately for distinct interstellar medium phases.

The chapter is organised as follows: In Section 5.1 we describe the properties of the simulation set-up used for this work, as well as the algorithm used to select the simulated galaxy sample and the region disk regions. Our main results are explored in Section 5.2, while we summarise and conclude our work in Section 5.3. The maps of the simulated galaxies used for this work are shown in Appendix A5. The tables summarising the estimates for our simulated galaxies and the observed samples used for comparison are reported in Appendix B5. We review the robustness of our results with respect to varying galaxy inclination in Appendix C5.

5.1 Methods

In this work we use the AZAHAR cosmological zoom-in simulations in the specific configuration RTnsCRiMHD. A full description of the AZAHAR RTnsCRiMHD setup is given in Section 4.4.

5.1.1 The simulated galaxy sample

For our analysis, we select a subset of galaxies from the AZAHAR catalogues (v4.7) corresponding to the population present in the simulation at $z = 3$. At this redshift, the simulation provides a population of galaxies spanning high star formation rates and star formation rate surface densities, comparable to those of local starburst systems, which

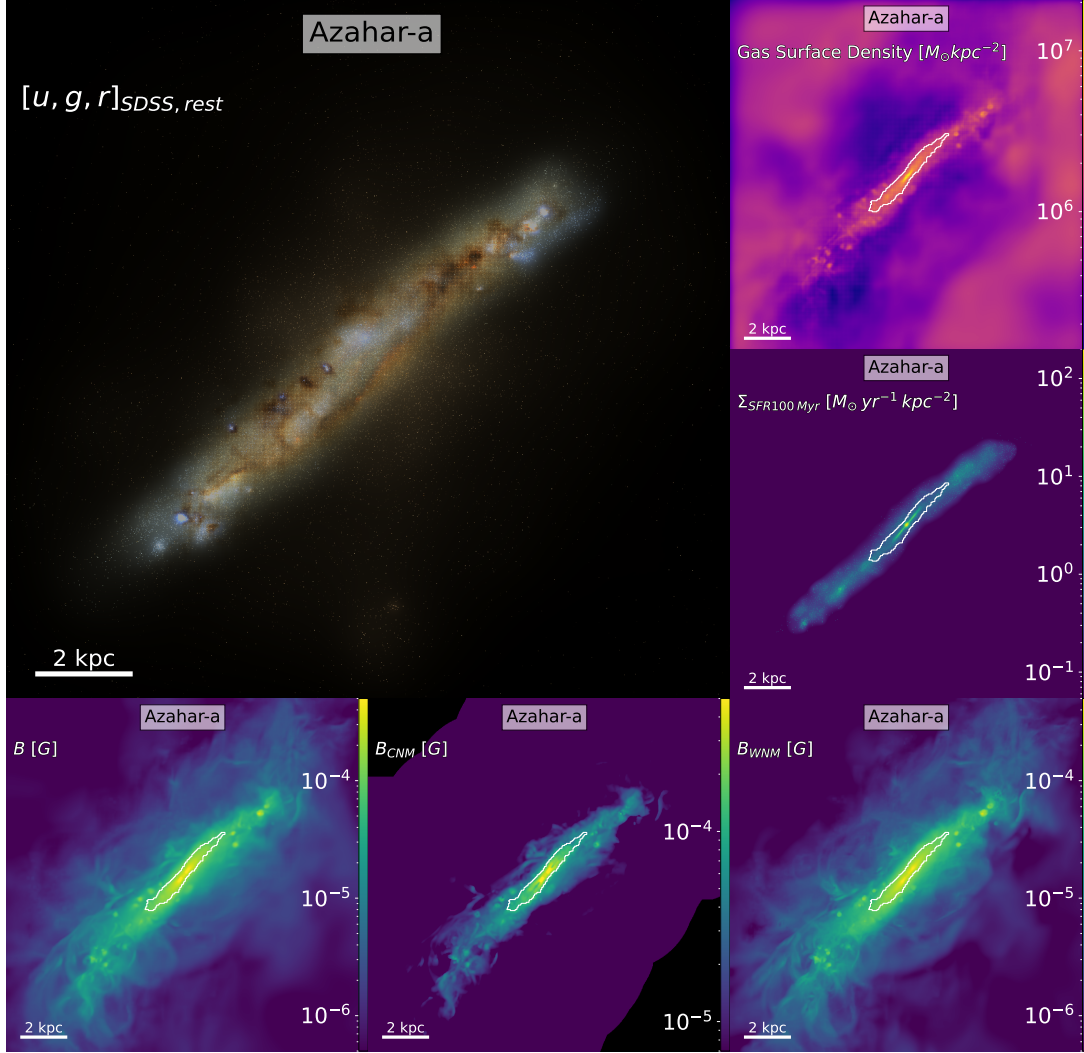


Figure 5.1. Multi-panel view of the simulated galaxy AZAHAR-A. The large left panel shows the rest-frame mock optical (SDSS *ugr*) image of the system. The two upper-right panels display the gas surface density and the star formation rate density, averaged over the past 100 Myr. The three bottom panels show the total magnetic field strength for the full gas, CNM, and WNM components. White contours in all panels mark the disk region adopted for the analysis.

would be rare at lower redshift in a cosmological volume of this size. These galaxies will be compared to an observational compilation of nearby systems spanning a wide range of star formation rates and morphologies (described in Section 5.2.1).

To ensure a consistent comparison with this observational sample, which spans star formation rates in the range $2.8 \times 10^{-3} < \text{SFR} < 155 \text{ M}_{\odot} \text{ yr}^{-1}$, we adopt a minimum SFR threshold of $10^{-3} \text{ M}_{\odot} \text{ yr}^{-1}$ and include all simulated systems with higher SFRs. Additionally, we want to identify similarities with the starburst galaxies in our polarisation observations, which are predominantly viewed edge-on. We therefore selected only edge-on projections of the simulated galaxies. This choice also facilitates a clean separation between the star-forming disk and the galactic outflow regions, which is essential for measuring the magnetic field structure in the disk. In this context, we excluded interacting systems and galaxies lacking a coherent rotating disk, since their disturbed morphologies prevent a reliable distinction between disk and outflow components. The edge-on orientation of the galaxy, as provided by the galaxy catalogues, corresponds to a line-of-sight perpendicular to a fixed, arbitrary vector and the angular momentum of the galaxy as computed from the total baryons, with their centring calculated using a shrinking spheres method (Martin-Alvarez et al., 2023). The final sample is therefore restricted to systems undergoing predominantly secular evolution. This selection yields a population of relatively stable, disk-dominated galaxies whose internal ISM properties are more directly comparable to those of star-forming galaxies in the local Universe.

The resulting sample consists of 19 galaxies with stellar masses $2.41 \times 10^8 \leq M_{\star}/\text{M}_{\odot} \leq 2.07 \times 10^{10}$ (median $1.05 \times 10^9 \text{ M}_{\odot}$, $\sigma = 4.5 \times 10^9$), star formation rates averaged over the past 100 Myr $1.22 \times 10^{-3} \leq \text{SFR}_{100}/(\text{M}_{\odot} \text{ yr}^{-1}) \leq 6.02$ (median 6.6×10^{-2} , $\sigma = 1.4$), specific star formation rates $4.63 \times 10^{-3} \leq \text{sSFR}_{100}/(\text{Gyr}^{-1}) \leq 8.51 \times 10^{-1}$ (median 7.6×10^{-2} , $\sigma = 1.7 \times 10^{-1}$), and SFR surface densities $1.5 \times 10^{-2} \leq \Sigma_{\text{SFR}}/(\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}) \leq 1.59$ (median 3.45×10^{-1} , $\sigma = 4.6 \times 10^{-1}$). In Appendix B5, Table 5.1 shows the unique galaxy ID, their stellar mass, star formation rates, specific star formation rates, and star formation rate density.

We compute projected maps for gas surface density, star formation rate surface density, density-weighted magnetic field strength, and total energies associated with magnetic fields, cosmic rays, thermal motions, and turbulence¹. For each quantity, we also generate ISM phase-separate maps by isolating the contributions from the cold and warm neutral media (CNM and WNM, respectively). Cells are separated into phases according to their temperature T and self-consistent hydrogen ionization state x_{HII}

¹Turbulent energies are computed following the small-scale motion separations described in (Martin-Alvarez et al., 2022).

following

- Cold neutral medium (CNM): $T \leq 200$ K;
- Warm neutral medium (WNM): $200 \text{ K} < T \leq 10^6 \text{ K}$, with the WNM gas density defined as the neutral fraction of the total warm gas density, $\rho_{\text{gas,WNM}} = \rho_{\text{gas,warm}} (1 - x_{\text{HII}})$;

as employed in [Martin-Alvarez et al. \(2024\)](#).

To separate the galaxy disk from galaxy outflows we use the gas surface density maps to define a disk mask for each galaxy. In order to define the mask, we follow the approach employed in section 2.3 of [Barnouin et al. 2023](#): we estimate a characteristic background level of diffuse gas from the surface density distribution, defined as the most populated bin in the intensity histogram. The disk region is then identified as the contiguous area where the gas surface density exceeds ten times this background level. This assures a robust noise estimation for galaxies with very different properties, such as size and gas surface density distribution.

As an illustrative example, Figure 5.1 presents a multi-panel view of the simulated galaxy AZAHAR-A, the most massive system in the AZAHAR suite. The large left panel shows the mock optical (*ugr*) image of the galaxy for reference. These are generated with our modified version of the SUNSET code², which produces synthetic broadband images by assigning Single Stellar Population (SSP) emission models to each stellar particle in the simulation, and mapping their emission through telescope-filter transmissivity curves. During this process, we also apply line-of-sight dust attenuation, computed from a 3D dust distribution. The two upper-right panels display the gas surface density and the star formation rate surface density averaged over the past 100 Myr. The three bottom panels show the magnetic field strength for the full gas, CNM, and WNM components. The white contours in the maps delineate the inner, star-forming galactic disk region. Figures 5.9 and 5.10 in Appendix A5 present the B field maps of the whole simulated galaxy sample in both the face-on and edge-on projection. The B field morphology is also shown through white streamlines calculated using the density-weighted magnetic field for the entire column displayed along the line-of-sight.

All physical quantities extracted from the simulations are analysed as follows, unless otherwise specified. Star formation rates extracted are measured on 100 Myr timescales, by selecting stellar particles with ages ≤ 100 Myr. The magnetic fields strength and specific energies measurements are computed on the disk regions of the simulated galaxies. We fit power-law relations $y = ax^b$ in log-log space using ordinary least

²SUNSET is part of the publicly available library within the RAMSES distribution.

squares (`numpy.polyfit`) within a paired bootstrap. Specifically, we draw $N_{\text{boot}} = 3000$ resamples of the (x, y) pairs with replacement; for each resample we refit $Y = A + bX$, where $Y \equiv \log_{10} y$, $X \equiv \log_{10} x$, and $A \equiv \log_{10} a$, and store the slope and intercept. The quoted slope and intercept values correspond to the median of their respective bootstrap distributions. The associated uncertainties are derived from the dispersion of these distributions. We also computed the central 95% prediction intervals, shown as a shaded band in the plots. Finally, per-point interquartile ranges (IQRs), defined as the interval between the 25th and 75th percentiles, are displayed as error bars in the plots for magnetic field strength estimates.

We outline the physical properties of our galaxy sample in Table 5.1, which shows the unique galaxy ID, their stellar mass, star formation rates, specific star formation rates, and star formation rate density. We show the median value of the magnetic field for the different gas phases for each galaxy in Table 5.2.

5.1.2 Magnetisation model variations

To assess the robustness of our results with respect to the magnetisation scenario, in addition to AZAHAR, we use a Milky Way-like cosmological simulation suite following the formation of a spiral galaxy under different magnetisation models (Martin-Alvarez et al., 2024). The initial conditions (ICs) for these simulations are the NUT ICs (Powell et al., 2011), studying a halo with dark matter mass $M_{\text{vir}}(z = 0) \simeq 5 \times 10^{11} M_{\odot}$. The simulation box is 12.5 cMpc per side, with a spherical zoom region of approximate diameter 4.5 cMpc. Its mass and stellar resolutions are $m_{\text{DM}} \simeq 5 \times 10^4 M_{\odot}$ and $m_{*} \simeq 5 \times 10^3 M_{\odot}$, respectively.

A full description of the galaxy formation physics in the models is provided in Martin-Alvarez et al. (2020) and Martin-Alvarez et al. (2021). In short, they feature the physics described above for the RTnsCRiMHD model of AZAHAR, with the exception of no radiative transfer and no cosmic rays. The suite of models employed here spans 4 simulations, each with a different magnetisation. Models labelled MB20 ($B_0 = 10^{-20} G$), MB11 ($B_0 = 10^{-11} G$), MB10 ($B_0 = 10^{-10} G$) have magnetic fields exclusively sourced through their ICs, with a uniform field of strength B_0 . In addition to $B_0 = 10^{-20} G$, the MBinj model also features magnetic fields injection through SNe, following the SN modelling described in Section 4.4.

5.2 Results

We measure the magnetic field strength relations with star formation activity across the AZAHAR sample, which spans star formation rates from $\text{SFR} = 1.22 \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1}$ to $6.22 \text{ M}_{\odot} \text{ yr}^{-1}$ and stellar masses from $M_{\star} = 2.41 \times 10^8$ to $2.07 \times 10^{10} \text{ M}_{\odot}$. The SFR and stellar masses of the sample are shown on Table 5.1. We compare our simulations with heterogeneous observational samples (Section 5.2.1), and discuss our inferred scalings in the context of the $\sim 1/3$ prediction by saturated dynamo models. We investigate the energetic relevance of magnetic fields in galactic disks, comparing the specific energies ($\mu_X \equiv U_X/M_{\text{gas}}$) for magnetic, thermal, turbulent, and CR components (Section 5.2.2). The magnetic field strength and specific energies scaling with star formation will be studied as function of the ISM phases (Section 5.2.3). Finally, we measure the magnetic field strength relation with star formation using the NUT models featuring seed field magnetisation (Section 5.2.4).

5.2.1 Magnetic fields versus star formation

To review the interrelation between the magnetic field across our population of galaxies in AZAHAR, we show the relation of their magnetic field strength (B) with the SFR in the top panel of Figure 5.2. Both the magnetic field strength and the SFR are measured within the same disk region defined in Section 5.1.1.

We find a scaling of magnetic field strength

$$B \propto \text{SFR}^{\alpha}, \quad \alpha = 0.28 \pm 0.08.$$

This relation is shown by the solid green line fit, with its 95% prediction interval as a shaded region.

We compare this result to estimates of the magnetic fields extracted from the literature. We selected four different samples of magnetic field strength estimations:

- **13 Starburst cores** from [Lacki & Beck \(2013\)](#). The magnetic field strengths were inferred from integrated GHz synchrotron emission arising predominantly from the central 0.1–1 kpc using the hadronic equipartition formalism presented in [Lacki & Beck \(2013\)](#), which accounts for pionic secondaries and strong bremsstrahlung losses. A unity filling factor is assumed, together with a steady-state proton-to-electron number ratio at GHz-emitting energies defined as $K \equiv n_{\text{CR,p}}/n_{\text{CR,e}}$, for which a value $K \simeq 100$ is adopted, a fiducial cosmic-ray spectral index $p \simeq 2.2$, and a cosmic-ray spectrum integrated up to $\gamma_{\text{max}} \rightarrow \infty$ (i.e. no explicit high-energy

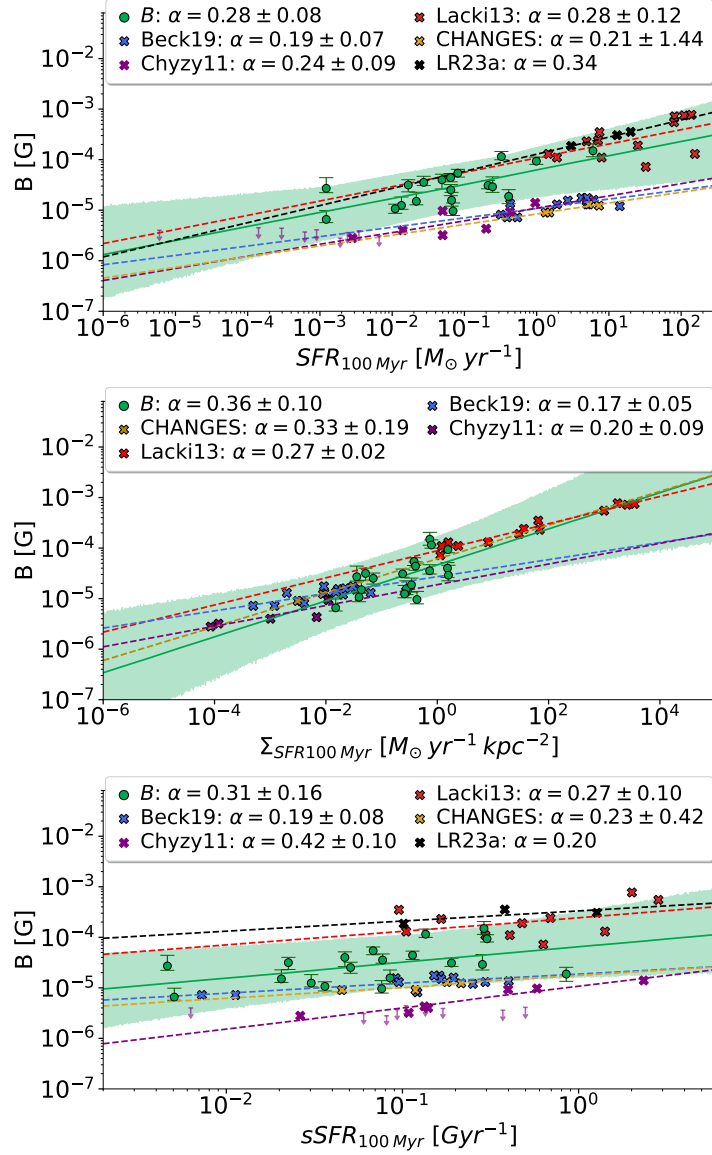


Figure 5.2. Magnetic field strength as a function of global star formation and mass indicators. Each panel shows the median magnetic field strength B within the disk mask of the simulated sample (green solid circles) measured as described in Section 5.1.1. Error bars show IQR range. The solid green line shows the best fit, and the shaded region indicates the 95% prediction interval, with their fitted slopes and the standard error reported in the legends. Samples of observed galaxies taken from the literature and their best-fit relations (dashed lines), are overlaid with different color crosses: red (Lacki & Beck, 2013), black (Lopez-Rodriguez, 2023), purple (Chyży et al., 2011), navy blue (Beck et al., 2019), and goldenrod (Heald et al., 2022; Stein et al., 2020, 2019; Mora-Partiarroyo et al., 2019, CHANGES survey). Their respective best-fit relations are shown as dashed lines. Upper limits from Chyży et al. (2011) are shown as downward arrows, and are excluded from the fits. Top: B versus integrated SFR over the last 100 Myr. Central: B versus the SFR surface density. Bottom: B versus sSFR.

cut-off is treated as a free parameter). With these assumptions, the resulting magnetic field strengths are numerically very similar to those obtained from the revised equipartition formula of Beck & Krause (2005). The values are shown as red crosses in the top panel of Figure 5.2.

- **7 Irregular dwarfs** from Chyży et al. (2011). These are low-mass systems ($1.05 \times 10^6 M_{\odot} \leq M_{\star} \leq 1.50 \times 10^9 M_{\odot}$). Magnetic field strengths were derived by integrating the radio flux density over apertures encompassing all detected radio emission (or the optical extent for non-detections) using the revised equipartition formalism of Beck & Krause (2005). A proton-to-electron number density ratio $K_0 = 100$ and a unity filling factor are assumed. The low- and high-energy cut-offs of the cosmic-ray spectrum ($E_{\min}$ and $E_{\max}$) are those implicit in the formulation and are not treated as free parameters. The effective path length is set by the line-of-sight extent of the galaxy. The resulting values characterise global, disk-averaged magnetic fields. Shown as purple crosses in the top panel of Figure 5.2.
- **12 Spiral galaxies** from Beck et al. (2019). Magnetic field strengths were estimated across the resolved disks using the revised equipartition formalism of Beck & Krause (2005). A proton-to-electron number density ratio $K_0 = 100$ and a unity filling factor are assumed, and the cosmic-ray energy cut-offs ($E_{\min}$ and $E_{\max}$) are those implicit in the formulation. For each galaxy, we adopt the median magnetic field strength across the disk, typically within $\sim 6\text{--}8$ kpc, as a representative global value. These points therefore characterise kpc-scale magnetic fields over the galaxy disks rather than nuclear regions. Shown as navy crosses in the top panel of Figure 5.2.
- **4 Edge-on spirals** from the CHANGES survey (Mora-Partiarroyo et al., 2019; Stein et al., 2019, 2020; Heald et al., 2022). Magnetic field strengths were derived from thermally corrected 1.5–6 GHz synchrotron maps, i.e. total intensity maps from which the free-free (thermal) radio emission estimated from extinction-corrected H α and infrared data was subtracted, using the revised equipartition formalism of Beck & Krause (2005). A proton-to-electron number density ratio $K_0 = 100$ and a unity filling factor were assumed. To account for the edge-on geometry, path lengths through the emitting medium are modelled geometrically and vary between ~ 6 and 20 kpc. The quoted values correspond to mean magnetic field strengths within ± 1 kpc of the midplane over the star-forming disks ($\sim 15\text{--}20$ kpc in diameter) at $\sim 10\text{--}15$ arcsec resolution ($\approx 0.8\text{--}1.5$ kpc). These values are

representative of kpc-scale averages across the galactic disks. Shown as yellow crosses in the top panel of Figure 5.2.

We also select **3 Starburst cores** (M82, NGC 253, NGC 2146) from [Lopez-Rodriguez \(2023\)](#). The magnetic fields strength in M82 were measured by the modified Davis-Chandrasekhar-Fermi method (DCF) ([Davis & Greenstein, 1951](#); [Chandrasekhar & Fermi, 1953](#)) accounting for large-scale flows by analytically solving the ideal-MHD equations ([Lopez-Rodriguez et al., 2021](#)). Magnetic fields for NGC 253 and NGC 2146 were then estimated by scaling from M82 using the empirical SFR–B relation $B = B_0 \text{SFR}^{0.34 \pm 0.04}$ with $B_0 = 128 \mu\text{G} (\text{M}_\odot \text{yr}^{-1})^{-0.34}$. We include these three systems as reference points for the magnetic field in the cold phase of the ISM at the core of starburst systems. Shown as black crosses on the top panel of Figure 5.2.

We stress that in this work we do not recompute magnetic field strengths from the radio data, but directly adopt the values published in the original studies in order to preserve their internally consistent treatment of synchrotron spectra, cosmic-ray physics, and source geometry. For each observational sample, we therefore retain the equipartition formalism, the proton-to-electron ratio, the filling factor, and the cosmic-ray energy integration limits as defined in the corresponding reference. We do not attempt to homogenise the assumed line-of-sight path lengths or emitting volumes across the different samples, as these correspond to physically distinct measurement regions (compact nuclear starbursts versus extended galactic disks and halos). Instead, we ensure that, within each sample, a self-consistent set of assumptions is adopted, and we interpret the observed differences in the normalisation of the B –SFR relations primarily in terms of the different spatial scales and physical environments probed by the various measurements.

For each galaxy of the observed sample, we selected an SFR tracer that is sensitive to star formation over the past ~ 100 Myr (e.g., FUV+22 μm , UV+IR, radio-based calibrations), approximately matching the SFR timescale employed for our simulated sample measurements.

The magnetic field strengths, SFRs, sSFR, Σ_{SFR} , SFR tracer, stellar masses, inclination, and references for the compiled observational sample are reported in Table 5.4.

It is worth noting that for the observational samples, the SFR and magnetic field measurements are not always obtained over identical physical regions. In particular, for compact starburst samples (e.g. [Lacki & Beck, 2013](#) and [Lopez-Rodriguez, 2023](#)), the magnetic field strengths refer to nuclear regions (typically $\lesssim 1$ kpc), while the SFR values adopted in this work are global, galaxy-integrated measurements compiled from the literature. Conversely, for nearby spirals ([Beck et al., 2019](#)), irregular dwarfs ([Chyży](#)

et al., 2011), and the CHANGES sample, both B and SFR broadly characterise the star-forming disk or the whole galaxy. This aperture mismatch in the starburst samples mainly affects the normalisation and increases the scatter of the B –SFR relation, but is not expected to significantly bias the fitted slopes.

We find the following slopes for the $B \propto \text{SFR}^\alpha$ relation for the observed samples:

- Starburst cores (Lacki & Beck, 2013): $\alpha = 0.28 \pm 0.12$.
- Irregular dwarfs (Chyży et al., 2011): $\alpha = 0.24 \pm 0.09$.
- Nearby spirals (Beck et al., 2019): $\alpha = 0.19 \pm 0.07$.
- Edge-on spirals (CHANGES): $\alpha = 0.21 \pm 1.44$.

We measure an approximately universal scaling of magnetic field strength in galaxies with their star formation rate $\alpha = 0.2–0.3$. This result is invariant across both simulated and observed measurements, as well as across the large variety of galactic environments and stages (e.g., nuclear region, starburst galaxies, dwarf galaxies, edge-on/face-on views).

The Lacki & Beck (2013) starbursts show a trend highly consistent with our simulations, even with SFR reaching significantly higher values than our simulated sample. For Chyży et al. (2011), Beck et al. (2019) and CHANGES samples, all show shallower slopes.

We find a scaling difference between samples, primarily in the normalisation of the B –SFR relation. We attribute these differences to the fact that the magnetic field strengths are measured over physically different regions of the galaxies.

Measurements from Lacki & Beck (2013) show a higher normalisation because their magnetic field strengths are derived within compact nuclear regions (~ 0.1 – 1 kpc), where the gas density, star formation activity, and associated turbulent and cosmic-ray energy densities are significantly higher. This is directly comparable to our simulated measurements, which are also extracted from the central ~ 0.5 – 1 kpc star-forming regions.

Conversely, the samples of irregular dwarfs (Chyży et al., 2011), nearby spirals (Beck et al., 2019), and edge-on spirals (CHANGES; Heald et al., 2022; Stein et al., 2020, 2019; Mora-Partiarroyo et al., 2019) show a systematically lower normalisation because their magnetic field strengths represent kpc-scale averages over the star-forming disk or the entire galaxy. Averaging over these extended regions includes large fractions of diffuse ISM and inter-arm or low-SFR areas, where the magnetic field and cosmic-ray energy

densities are lower, thus reducing the global, disk-averaged magnetic field strength at a given global SFR.

To verify that the inferred magnetic field–star formation scaling is not driven by projection effects, we perform a complementary analysis using face-on projections of the simulated galaxies. The resulting B–SFR relations are fully consistent with those obtained from edge-on views, demonstrating that the measured scaling is independent of galaxy inclination. The face-on analysis is presented in Appendix C5, with the corresponding relations shown in Figure 5.11.

Magnetic field strength versus SFR surface density

As discussed in Section 1.4, the standard interpretation of the B –SFR correlation arises from equipartition between SN-driven turbulence and magnetic energy. Under the assumption of the magnetic energy being amplified to some fraction of saturation, f_{sat} , of the turbulent energy, [Schleicher & Beck \(2013\)](#) derives a scaling $B \propto \Sigma_{\text{SFR}}^{1/3}$.

In the central panel of Figure 5.2, we show our measured $B \propto \Sigma_{\text{SFR}}^\alpha$ relation for the simulated sample. The star formation surface density is measured in the same innermost region of our galaxies, using the semi-major axes of the disk region and following the approach used in [Wiegert et al., 2015](#) for their measurements. Our galaxies follow a scaling $\alpha = 0.36 \pm 0.10$, in good agreement with a SN-driven turbulence assumption.

We compare the results with the observed samples. In the case of the CHANGES galaxies, we used the Σ_{SFR} values directly reported in the same works where the magnetic field strengths were derived ([Heald et al., 2022](#); [Stein et al., 2020, 2019](#); [Mora-Partiarroyo et al., 2019](#)). For the remaining samples, we estimated the star formation rate surface density, Σ_{SFR} , by dividing the total SFR of each galaxy by the area of the region where the magnetic field strength was measured. In each case, we used the aperture radius reported in the corresponding study to define this circular area.

This approach is subject to several caveats. The SFR values compiled from the literature represent integrated measurements which are not necessarily computed over the same physical region as the magnetic field. To first order, we assume that the SFR is approximately uniform across the disk area encompassing the magnetic field measurement. In practice, spatial variations in the local SFR, particularly between central starburst regions and outer disks, may introduce systematic uncertainties in Σ_{SFR} . Nevertheless, this method provides a reasonable first-order estimate that enables a meaningful comparison between simulated and observed galaxies.

The observed samples show the following scaling of magnetic field with Σ_{SFR} :

- Starburst cores ([Lacki & Beck, 2013](#)): $\alpha = 0.22 \pm 0.02$.

- Irregular dwarfs (Chyży et al., 2011): $\alpha = 0.20 \pm 0.09$.
- Nearby spirals (Beck et al., 2019): $\alpha = 0.17 \pm 0.05$.
- Edge-on spirals (CHANGES): $\alpha = 0.33 \pm 0.19$.

The Lacki & Beck, 2013 starburst cores are consistent with saturation of the small-scale dynamo in dense, high-pressure nuclei. Edge-on spirals (CHANGES) are consistent with the $1/3$ expectation within large uncertainties ($\alpha \approx 0.33 \pm 0.19$) due to the limited number of sources of this sample. The nearby spirals from Beck et al. (2019) and irregular dwarfs from Chyży et al. (2011) show a shallower slope similar to their global B - SFR relation, likely reflecting their low star formation efficiencies and turbulent energy budgets.

All observational trends lie within the 95% prediction interval of our fit, reinforcing a robust B - Σ_{SFR} coupling across galaxy types and measurement strategies.

Magnetic field strength versus specific SFR

To understand the effect of the mass on the B and SFR relation, we examine this dependence across in our simulated galaxies in Figure 5.3.

For each simulated galaxy, the stellar mass $M_\star$ is computed from the projected stellar mass maps by summing the stellar mass contained in all pixels belonging to the main galaxy body. To avoid contamination from interacting companions or nearby satellite systems, we construct a custom spatial mask on the stellar mass maps that isolates the primary galaxy and excludes secondary structures visible in projection. Since $M_\star$ is used only as a global, integrated quantity, small variations in the exact mask boundary have a negligible impact on the resulting stellar mass.

The sample follows a tight correlation between the magnetic field strength B and stellar mass $M_\star$,

$$B \propto M_\star^{0.61 \pm 0.15}.$$

reflecting how part of the scaling measured for the B -SFR plane is driven by galaxy stellar mass.

A simple energetic argument shows this is plausible. If turbulent kinetic and magnetic energies remain in rough equipartition and scale with the potential depth, then at a fixed radius r one expects

$$B(r) \propto \sqrt{\frac{G M(< r)}{r} \rho_{\text{gas}}} \sim \sqrt{\rho_{\text{gas}}} v_c(r), \quad (5.1)$$

so that, for modest variations in ρ_{gas} at fixed r , B should scale approximately as $M_{\star}^{1/2}$, consistent with our best-fit slope. This scaling can also be rewritten as a function of the circular velocity (v_c) of such systems. This is qualitatively aligned with observations that more massive, faster-rotating disks host stronger large-scale fields (via the Tully–Fisher connection between v_{rot} , dynamical mass, and $M_{\star}$; Reyes et al. 2011; Tabatabaei et al. 2016) and with galaxy-formation simulations where central B grows with bulge mass and central gas density.

We test if the observed samples show this correlation, using stellar masses estimates taken from various sources from the literature, as listed in Table 5.4. We find:

- Beck et al. (2019): $\alpha = -0.00 \pm 0.19$
- Lacki & Beck (2013): $\alpha = -0.20 \pm 0.21$
- Chyży et al. (2011): $\alpha = 0.08 \pm 0.41$
- CHANGES sample: $\alpha = 0.16 \pm 3.27$

Within uncertainties, all observed samples are consistent with a flat B – $M_{\star}$ relation, with little dependence of the magnetic field strength on total stellar mass. However, these trends can be explained by the methodology employed to measure the magnetic field strength in the observed samples. In all observational compilations, the stellar masses are integrated over the entire galaxy, while magnetic field strengths are derived from radio synchrotron emission measured within specific apertures of regions with considerably different sizes and physical conditions:

- **Central (starburst-core) measurements.** In the starburst sample of Lacki & Beck (2013), the radio flux is explicitly restricted to compact nuclear regions, intentionally weighting the densest, most CRs rich gas and yielding the highest inferred magnetic field strength values. One extreme case is Arp220, an ultra-luminous infrared galaxy with two merger nuclei of 200 pc in size separated by 300 pc Barcos-Muñoz et al. (2015). Due to the merger, the strong star formation activity, and molecular outflows, this galaxy has been measured to have one of the strongest, mG, magnetic field strength McBride et al. (2014). This outlier may be biasing the fitting to show a negative correlation using the Lacki & Beck, 2013 sample. However, note that this sample is composed of starburst galaxies, which agree with the trend found in the simulated galaxies.
- **Whole-galaxy / disc averages.** In nearby spirals, magnetic field strength is estimated from total or ring-averaged synchrotron intensities using the revised

equipartition formula (Beck & Krause, 2005), which mixes the relatively small area corresponding to bright centres with extended and fainter outer discs. This measuring procedure leads to a lower mean B than the central measurements, and flattens trends with $M_\star$ due to increasing r and a non-spherical configuration. For a dex increase in stellar mass of disk galaxies, the expected variation of B is approximately a factor of two, consistent with the observed shallow scalings. CHANGES edge-on systems likewise report kpc-scale, disc-averaged fields from thermally corrected 1.5–6 GHz maps under revised equipartition.

- **Local Group dwarfs.** Chyży et al. (2011) derive magnetic field strength from single-dish maps, integrating over each galaxy’s optical extent. For compact starburst dwarfs such as IC 10 the flux is core-dominated; for more extended dwarfs the estimate approximates a global mean field.

Because $M_\star$ is always a global, integrated quantity while the typical measurement of magnetic field strength is effectively density-weighted within the radio aperture, the two quantities are not directly comparable. Variations in the B -measurement aperture (core-only vs. whole disc) and the mass aperture (whole galaxy) weakens or cancels the intrinsic B –mass coupling and produces flat slopes when samples are mixed or contain bulge-disk component variations. In practice, central/core measurements (Lacki & Beck, 2013; and our synthetic maps) yield higher normalizations at a given $M_\star$; whereas whole-disc averages (e.g. nearby spirals) yield lower normalizations and flatter trends. We note that for dwarf galaxies, the same trend may still take place with the HI mass (and/or the velocity dispersion σ_v) of the galaxies, possibly modulated by galaxy outflows (Chyży et al., 2011). This poses measuring magnetic fields in dwarf galaxies as the most promising avenue to fully-characterise whether the scaling proposed by Eq. 5.1 holds.

To determine the relative importance of star formation, and remove mass-driven effects in its relation with B , we review the magnetic field strength as a function of specific SFR ($\text{sSFR} \equiv \text{SFR}/M_\star$). This is shown in the bottom panel of Figure 5.2.

Our simulated galaxies show the relation

$$B \propto \text{sSFR}^\alpha, \quad \alpha = 0.31 \pm 0.16.$$

The Lacki & Beck (2013) measurements in the core regions of starburst galaxies exhibit a very similar slope with a tighter correlation ($\alpha = 0.27 \pm 0.10$), and stronger magnetisations. Both nearby spirals ($\alpha = 0.19 \pm 0.08$) studied by Beck et al. (2019) and by the CHANGES collaboration (Stein et al., 2019; Mora-Partiarroyo et al., 2019;

Stein et al., 2020; Heald et al., 2022; $\alpha = 0.23 \pm 0.42$) exhibit somewhat shallower scaling, and a weaker norm for their magnetic field strength. Conversely, the dwarf galaxies measured by Chyży et al. (2011) have the steepest correlation ($\alpha = 0.42 \pm 0.10$), although with the weakest field strength. All of the observed samples and our simulated galaxies, however, are consistent within $1\text{-}\sigma$. Interestingly, expressing the magnetic field strength interrelation with star formation in specific terms yields the largest separation between datasets, both in terms of power-law indices variation and normalizations.

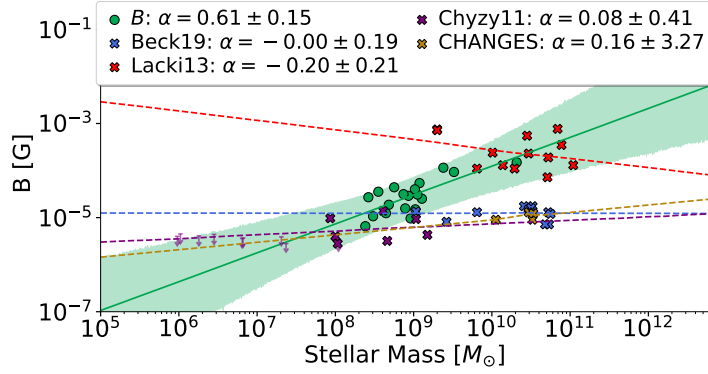


Figure 5.3. Magnetic field strength as a function of stellar mass $M_\star$ (solid green circles). The solid green line shows the best fit, and the shaded region indicates the 95% prediction interval, with the fitted slopes and the standard error reported in the legend. Samples of observed galaxies taken from the literature and their best-fit relations (dashed lines), are overlaid with different colour crosses: red (Lacki & Beck, 2013), black (Lopez-Rodriguez, 2023), purple (Chyży et al., 2011), navy blue (Beck et al., 2019), and goldenrod (Stein et al., 2019; Mora-Partiarroyo et al., 2019; Stein et al., 2020; Heald et al., 2022, CHANGES survey). Their respective best-fit relations are shown as dashed lines. Upper limits from Chyży et al. (2011) are shown as downward arrows, and are excluded from the fits.

5.2.2 Specific energy budgets versus SFR

In the previous sections, we showed how the star formation activity in the disks of galaxies is tightly correlated with magnetic field strength, suggesting a scenario in which star formation is driving magnetic field amplification in galaxies. Since our MHD simulations make no a priori equipartition assumptions between turbulent and magnetic energy, the correlation arises self-consistently from SN-driven turbulence and MHD amplification. This indicates a coupling between turbulent kinetic and magnetic energies across the phases of the ISM that needs to be further characterized.

We examine the relationship between the total SFR and the specific energy (i.e., the

energy per unit gas mass) for the full gas content of the simulated galaxies. Figure 5.4 shows these relationships, where different colour points indicate the specific energy $\mu \equiv U/M_{\text{gas}}$ of the magnetic (blue), thermal (grey), turbulent (red), and cosmic ray (yellow) components. Specific energies are computed as the total energy in each component integrated over the galactic disk, and divided by the corresponding total gas mass in the same region. The dotted lines show bootstrap-based best-fit power-law relations for each energy component. The specific energy values for each galaxy of the sample are shown on Table 5.3.

All energy components exhibit a positive correlation with star formation, both for absolute and sSFR. This indicates that more actively star-forming galaxies tend to have higher specific energies. The thermal ($\alpha_{\text{therm}} = 0.15 \pm 0.11$), cosmic ray ($\alpha_{\text{CR}} = 0.14 \pm 0.10$) and turbulent ($\alpha_{\text{turb}} = 0.11 \pm 0.21$) energy components show similar scalings with sSFR. These slopes indicate a self-regulated energy content, moderately sensitive to star formation, and consistent with a scenario where CRs, turbulent and thermal energy are replenished by SN feedback during secular evolutions. Note that the galaxies selected are not undergoing mergers.

The magnetic specific energy $\mu_{\text{mag}} \equiv U_{\text{mag}}/M_{\text{gas}}$ scales most steeply with both SFR ($\alpha_{\text{mag}} = 0.62 \pm 0.15$) and sSFR ($\alpha_{\text{mag}} = 0.71 \pm 0.30$). This scaling leads to sub-equipartition magnetisations in galaxies with low star-formation activity and approximate equipartition in those with ongoing star formation, with the transition occurring around $\text{sSFR} \sim 0.1 \text{ Gyr}^{-1}$ and $\text{SFR} \sim 1 \text{ M}_{\odot} \text{ yr}^{-1}$. This steep scaling reinforces our findings for the B -SFR relations: since $\mu_{\text{mag}} \propto B^2/\rho_{\text{eff}}$, where ρ_{eff} denotes the effective gas density associated with the region over which the magnetic energy is averaged, and $B \propto \text{SFR}^{0.28 \pm 0.08}$, one expects $\mu_{\text{mag}} \propto \text{SFR}^{0.56 \pm 0.16} \rho_{\text{eff}}^{-1}$. The measured α_{mag} suggests a scenario where turbulence driven by supernova feedback couples to magnetic fields through small-scale dynamo processes. (Kulsrud, 1999; Schleicher & Beck, 2013; Federrath, 2016; Martin-Alvarez et al., 2018; Pakmor et al., 2023).

These trends are consistent with a self-regulated ISM picture. In the inner, star-forming disk of neutral gas, the turbulent energy fraction remains approximately constant, as expected for self-regulated star formation with nearly constant gas velocity dispersions (e.g., Ostriker & Shetty 2011; Krumholz & Burkhardt 2016; Varidel et al. 2020). The CRs energy fraction increases sub-linearly with sSFR, since injection scales proportionally to SFR but it is reduced by short CR residence times (e.g., Lacki 2013). The thermal energy fraction increasing weakly with sSFR, likely due to efficient radiative cooling maintaining thermal balance in the denser ISM (e.g. Wolfire et al. 2003). Finally, the magnetic energy fraction increases most rapidly with sSFR, through increased coupling

with the kinematic components (Schleicher & Beck, 2013; Martin-Alvarez et al., 2022; Pakmor et al., 2024), and eventually reaching approximate equipartition at high sSFR values. This magnetic pressures is comparable to the thermal and turbulent terms, implying a dynamically important magnetic component, with important consequences for vertical support, feedback coupling, and wind launching (e.g., Heesen et al. 2011; Pillepich et al. 2018; Su et al. 2020; Martin-Alvarez et al. 2020).

It is worth emphasising that the linear fits reported here should not be extrapolated to high SFRs ($> 100 \text{ M}_{\odot} \text{ yr}^{-1}$). The small-scale dynamo saturates once Lorentz forces back-react on the flow, limiting further field amplification and field line stretching (e.g., Schleicher & Beck 2013; Martin-Alvarez et al. 2022; Pakmor et al. 2024). Beyond this point, the magnetic energy is expected to approach equipartition with the turbulent component, and the magnetic slope should gradually converge toward that of the turbulent energy, corresponding to a state where magnetic, turbulent, and thermal pressures remain in near balance.

While our simulations favour a scenario in which magnetic field amplification is primarily regulated by supernova-driven turbulence through small-scale dynamo processes, it is worth highlighting that the resulting B field configurations are not restricted to purely tangled, small-scale structures. Across the full sample of simulated galaxies included in our analysis, several systems exhibit ordered, spiral-like magnetic field patterns on kiloparsec scales in their face-on projections (see Figure 5.10). This indicates the presence of a large-scale magnetic field component, driven by differential rotation and shear. In the corresponding edge-on projections (see Figure 5.9), the B field appears predominantly aligned with the disk midplane.

Nevertheless, the presence of ordered magnetic field structures should not be interpreted as evidence for the operation of a dominant large-scale mean-field dynamo. The field morphology does not exhibit a well-defined vertical parity or symmetry with respect to the disk midplane, which would be expected for a fully developed, mature large-scale mean-field α - Ω dynamo (Ntormousi et al., 2020). When selecting only gas cells associated with galactic outflows, defined by an escaping velocity threshold of $v_{\text{out}} > 50 \text{ km s}^{-1}$, the edge-on magnetic field streamlines appear more open and vertically extended. These features still do not display a coherent symmetry or polarity pattern that would point to a dominant large-scale dynamo operating in the disk.

Furthermore, we find that the mean toroidal magnetic field in the disks of our sample of simulated galaxies is weaker than the spatial fluctuations of the magnetic field strength, with typical ordered-to-turbulent ratios of $\sim 5\%$ up to $\sim 20\%$, indicating dominance of a turbulent magnetic component. While this suggests that a large-scale

dynamo does not dominate in these highly star-forming systems, our findings do not address its importance during stages of lower relative star formation activity.

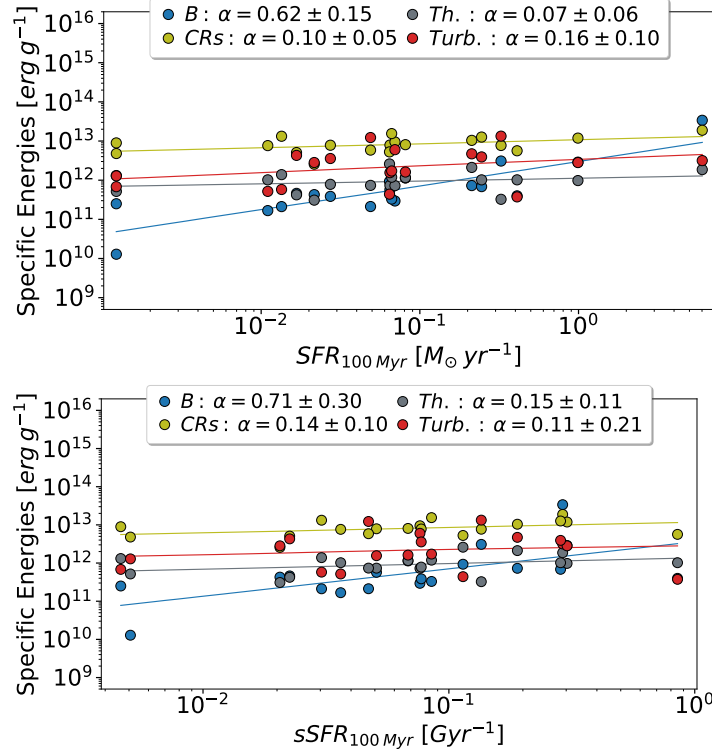


Figure 5.4. Specific energies as a function of the SFR (top panel) and sSFR (bottom panel). Each point represents the specific energy associated to the magnetic (blue), thermal (grey), turbulent (red) and cosmic ray (yellow) component within the disk of each galaxy. The best fits for each energy component are shown as coloured lines, with their corresponding slopes and standard errors provided in the legends.

5.2.3 The dependence of gas phase magnetisations and energy fractions on star formation

In Section 5.2.2, we showed that the magnetic field strength in the disks of spiral galaxies increases with star formation, reaching approximate magnetic equipartition with the thermal and turbulent components for systems with significant ongoing star formation (sSFR $\gtrsim 0.1$ Gyr⁻¹, SFR $\gtrsim 1$ M_⊙ yr⁻¹; Section 5.2.2).

A global analysis of this magnetisation provides only a limited picture, as colder ISM phases are expected to have higher relative magnetisations (Ferrière, 2001; Draine, 2011; Crutcher, 2012). To understand this increased relevance of magnetic fields across ISM phases, we now extend this analysis to the CNM and WNM phases. The upper

panel of Figure 5.5 shows the same B -SFR relation previously shown in Figure 5.2 (top left), now for the CNM values in blue and WNM values in orange. The best-fit power laws are shown as colour-coded solid lines, with the shaded areas indicating 95% prediction interval. Both phases show significant positive and comparable trends:

$$\alpha_{\text{CNM}} = 0.28 \pm 0.08$$

$$\alpha_{\text{WNM}} = 0.29 \pm 0.10.$$

These broadly similar slopes suggest that the same underlying mechanism operates across phases in the disk, especially when compared with the scaling obtained for the entire gas distribution ($\alpha = 0.28 \pm 0.08$).

The bottom panel of Figure 5.5 shows the B -sSFR relation for the cold and warm neutral media (CNM in blue; WNM in orange). The fitted power-law indices are

$$\alpha_{\text{CNM}} = 0.32 \pm 0.15$$

$$\alpha_{\text{WNM}} = 0.30 \pm 0.19.$$

Within uncertainties, the two phases are consistent with each other, and once again in agreement with the global scaling ($\alpha = 0.31 \pm 0.16$).

The approximate phase-independence of the B -SFR/sSFR scalings suggests that the same processes regulating magnetic field strength operate across the CNM and WNM neutral phases.

CNM. We show in Figure 5.6 the scaling of the specific energies in the CNM as a function of SFR (top panel) and sSFR (bottom panel). Here we focus our analysis on the scalings between the different energy components and the specific star formation. The power-law indices between each energy component and the integrated SFR follow comparable trends and are shown in the figure. The specific magnetic energy has the steepest scaling with sSFR ($\alpha_{\text{mag,CNM}} = 0.74 \pm 0.29$), followed by the CRs component ($\alpha_{\text{CR,CNM}} = 0.42 \pm 0.14$) and the turbulent component ($\alpha_{\text{turb,CNM}} = 0.14 \pm 0.28$). The thermal specific energy ($\alpha_{\text{therm,CNM}} = -0.06 \pm 0.07$) follows a slight decrease with increasing sSFR.

Energetically, most of our galaxies are turbulence-dominated in the CNM, with non-negligible contributions from the CRs component. The magnetic component is only significant on the high sSFR end, reaching approximate equipartition with the other energy forms for $\text{sSFR} \gtrsim 0.1 \text{ Gyr}^{-1}$ and for $\text{SFR} \gtrsim 1 \text{ M}_{\odot} \text{ yr}^{-1}$. As star formation in our simulations takes place almost exclusively in the CNM gas, this reflects a scenario

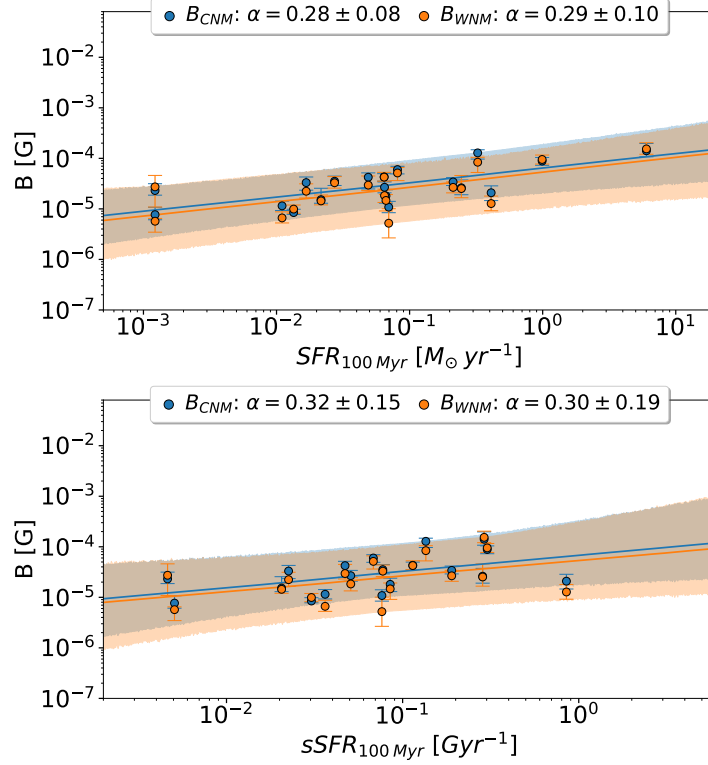


Figure 5.5. Magnetic field strength versus global star formation for neutral ISM phases. Panels show the median magnetic field strength B within the disk mask of the simulated sample (solid circles) in the CNM (blue) and WNM (orange) phases. Error bars for each data point show the IQR for each galaxy. Solid lines indicate best-fit power laws, and the shaded region indicates the 95% prediction interval; fitted slopes are reported in the legends. Top-panel: B versus integrated SFR. Bottom-panel: B versus specific SFR (sSFR).

where higher sSFR values can increase the magnetic contribution up to equipartition. However, this energy component cannot significantly exceed the energy budget of the other components, as this would suppress star formation. This behaviour is observed in galaxies with unrealistically strong magnetic field strengths, $B_{10} = 10^{-10}$ G, in the NUT simulations (Martin-Alvarez et al., 2018, 2020). The slight decrease in thermal energy with increasing sSFR can be similarly interpreted as colder, denser gas clouds will feature more efficient star formation. Successful star-forming regions will in turn significantly increase gas temperatures either through photoheating ($\sim 10^4$ K) or SN feedback ($\gtrsim 10^6$ K), and their gas will no longer be classified as CNM (Martin-Alvarez et al., 2023).

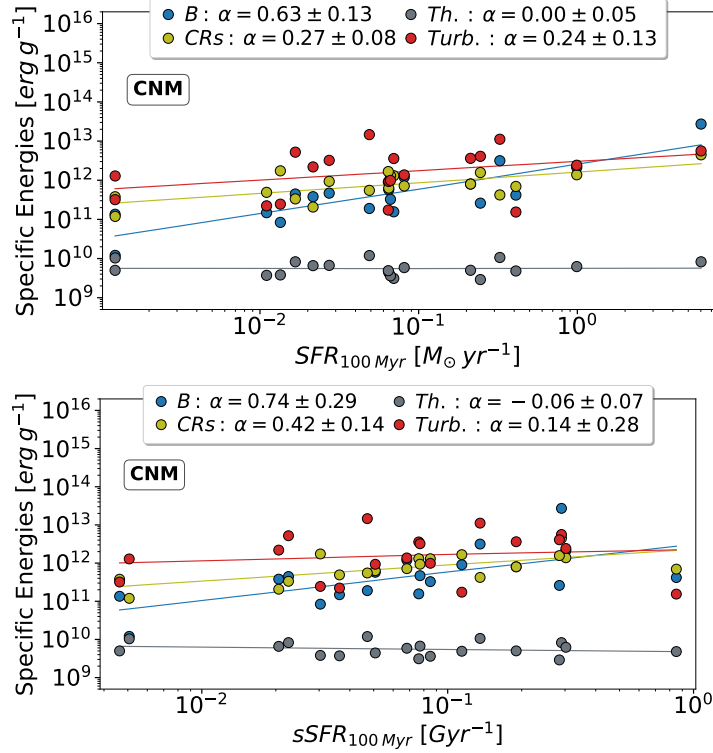


Figure 5.6. Specific energies as a function of the star formation rate (SFR) over the last 100 Myr (top panel) and over the specific star formation rate (bottom panel) in the CNM phase. Each point represents the specific energy associated to the magnetic (blue), thermal (grey), turbulent (red) and cosmic ray (yellow) component within the disk mask of each galaxy. The best fit for each energy component associated to each component is shown as a dotted line, with the slope and Pearson index shown on the legend on the top.

WNM. Figure 5.7 shows again the scaling of the specific energies, now for the WNM. The top panel shows these quantities as a function of the SFR, whereas the bottom panel shows them as a function of the sSFR. While the scalings of the specific energies still follow similar approximate trends, they are broadly shallower for the WNM phase. The magnetic component ($\alpha_{\text{mag,WNM}} = 0.68 \pm 0.32$) is approximately unchanged. The CR component is now shallower ($\alpha_{\text{CR,WNM}} = 0.31 \pm 0.11$), likely as a result of higher hadronic energy losses for CRs in the denser CNM gas. The turbulent component ($\alpha_{\text{turb,WNM}} = 0.07 \pm 0.20$) features only a very shallow correlation with sSFR, in agreement with SN-driven energy injection taking place at ~ 100 pc scales, and in the WIM and hot phases; and subsequently cascading down into the WNM (Korpi et al., 1999; Joung & Mac Low, 2006; Martin-Alvarez et al., 2022). The thermal specific energy ($\alpha_{\text{therm,WNM}} = 0.0 \pm 0.09$) is approximately independent to the sSFR across the inner star-forming disk of the sampled galaxies.

Unlike for the CNM, the WNM thermal energy provides a significant contribution to the total energy: at low SFR it can be near or above the magnetic energy (e.g. in 886xp574558438, g8, 719xp463552479, 1478xp591488450), and in rough equipartition with the turbulent and CR components. However, for $\text{sSFR} \gtrsim 0.1 \text{ Gyr}^{-1}$, the non-thermal components strengthen relative to the thermal one, and the magnetic term overtakes the thermal term.

Across both phases, the combination of a steep μ_{mag} rise with SFR, a weak trend for μ_{turb} , and approximately flat μ_{thermal} leads to galaxies that become increasingly magnetically dominated once $\text{SFR} \gtrsim 1 \text{ M}_{\odot} \text{ yr}^{-1}$ and $\text{sSFR} \gtrsim 0.1 \text{ Gyr}^{-1}$, with this trend being more pronounced in the CNM.

5.2.4 Model Dependence of the B –SFR Relation: Seeds vs. SN Injection

To assess how the B –SFR relation depends on seed magnetisation and on the injection prescription, we analyse a single Milky-Way like NUT galaxy simulated with different initial magnetic configurations (see Section 5.1.2 for the details of the NUT simulation set-up). Each point along a given run corresponds to a different epoch (thus different SFR), so trends reflect the joint evolution in z and activity. We compare three runs with primordial seed fields of amplitude $B_0 = 3 \times 10^{-X} \text{ G}$ (hereafter MBX, with $X = 10, 11, 20$) and one run with SN magnetic injection (MBinj), which adopts the same prescription used in our main sample. The data and power-law fits are shown in Fig. 5.8 for both the SFR (top panel) and sSFR (bottom panel).

We find the following slopes for the different magnetisation models:

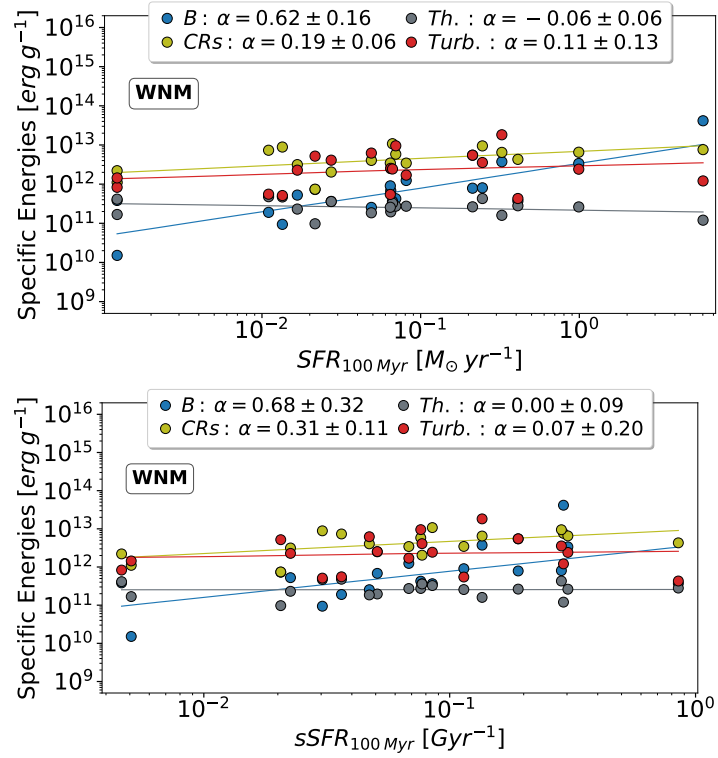


Figure 5.7. Same as Figure 5.6, now shown for the WNM phase.

- **MB10:** $\alpha_{\text{SFR}} = 0.00 \pm 0.21$, $\alpha_{\text{sSFR}} = -0.06 \pm 0.15$,
- **MB11:** $\alpha_{\text{SFR}} = 0.10 \pm 0.07$, $\alpha_{\text{sSFR}} = 0.10 \pm 0.06$,
- **MB20:** $\alpha_{\text{SFR}} = 0.52 \pm 0.11$, $\alpha_{\text{sSFR}} = 0.48 \pm 0.09$.
- **MBinj:** $\alpha_{\text{SFR}} = 0.32 \pm 0.10$, $\alpha_{\text{sSFR}} = 0.29 \pm 0.07$.

These slopes reveal differences in the magnetic response to star formation among the various seed configurations. Models with high primordial seeds produce shallow slopes (consistent with 0–0.1), as expected once the dynamo saturates early: after saturation, B varies only weakly with instantaneous SFR, since magnetic energy has already reached near-equipartition with the turbulent component.

The MB20 model has the larger scaling with star formation activity with SFR, but with very low absolute values in magnetic field strength ($< 10^{-14} G$). The steep MB20 slope is consistent with a pre-saturation small-scale dynamo: B is still amplified efficiently by turbulent motions, so it responds more strongly to changes in SFR/sSFR than it would in the saturated/equipartition regime, where the slope is expected to flatten.

The SN-injected run (MBinj) is fully consistent with our main spirals and with saturated small scale dynamo expectations, supporting the physical fidelity of the injection model.

Overall, these results suggest that within a single galaxy the B –SFR slope is set by the state of the small-scale dynamo. Strong seeds or continuous SN injection bring the system to saturation early and yield shallow α (MB10/MB11) or the canonical $\alpha \approx 0.3$ (MBinj). Extremely weak seeds (MB20) stay kinematic longer, producing steep slopes but negligible absolute field strengths.

5.3 Conclusions

In this chapter, we investigated the interrelation of magnetic fields scale with star-formation activity in spiral galaxies. We used the AZAHAR simulation suite (Martin-Alvarez et al. in prep) “full-physics” models, incorporating radiative transfer, cosmic rays and magnetism with state-of-the-art star formation and SN feedback models. We selected a sample of secularly evolving, disk galaxies with $10^{-3} M_{\odot} \text{ yr}^{-1} \lesssim \text{SFR}_{100} \lesssim 10 M_{\odot} \text{ yr}^{-1}$ and stellar masses $10^8 M_{\odot} \lesssim M_{*} \lesssim 10^{10} M_{\odot}$, corresponding to $z \sim 3$ analogues of local starburst galaxies. For these systems, we generated edge-on measurements of various quantities, focusing on their inner star-forming disk (with typical major axis of ~ 0.5 kpc). We compared our results with observed samples (Chyży et al., 2011; Lacki &

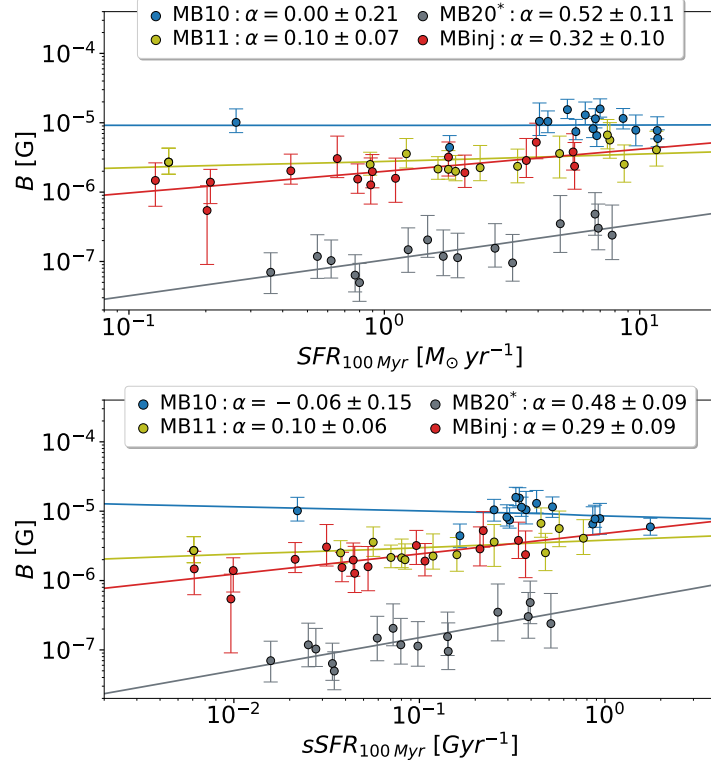


Figure 5.8. Magnetic field strength B versus star-formation rate (top panel) and specific star formation rate (bottom panel) for a NUT galaxy with different magnetisation prescriptions. MBX runs adopt primordial seed fields of $B_0 = 3 \times 10^{-X}$ G, while MBinj includes supernova magnetic injection. Solid lines show best-fit power laws. Error bars represent IQR computed for each galaxy.

*The magnetic field estimates of the MB20 model have been multiplied by 10^7 for better visualisation.

Beck, 2013; Beck et al., 2019; Stein et al., 2019; Mora-Partiarroyo et al., 2019; Stein et al., 2020; Heald et al., 2022), across ISM neutral phases (CNM/WNM). We tested the robustness of our results by reviewing this trends with an additional simulation suite of a Milky Way-like spanning multiple degrees and channels of magnetisation (Martin-Alvarez et al., 2021). Our main findings are:

- We find an approximately universal scaling of magnetic field strength with star formation rate in galaxies ($\alpha \sim 0.2 - 0.3$). This scaling is preserved across galaxy masses (from dwarf to spiral galaxies), inclinations, neutral phases (CNM and WNM), and galactic environments.
- The star formation surface density follows the expectation for SN-driven ISM turbulence, and turbulence-regulated magnetic field strength ($\alpha_{\Sigma} \sim 1/3$; Schleicher & Beck 2013). Remarkably, when expressed in terms of Σ_{SFR} , all systems align along the common sequence defined by our simulated galaxies, independent of their individual slopes.
- The B -sSFR relation provides the largest segregation between environments and galaxy types, both in terms of magnetic field strength normalization and its power-law index. All systems, however, remain broadly consistent with a common scaling of $\alpha \sim 0.3$.
- All energy components (i.e., turbulent, magnetic, CRs, and thermal) in our simulated galaxies increase with star formation, with the magnetic energies displaying the steepest dependence. While these trends are both present in both the CNM and WNM phases, we measure a steeper increase of the CRs and turbulent components with sSFR in the CNM phase.
- Overall, our CNM and WNM gas phases are primarily dominated by the turbulent energy component, followed by the CRs energy, and with a more negligible contribution of the thermal energy in the WNM. Following the steepness of the magnetic energy with sSFR, we find the magnetic energy to range from sub-dominant at low star formation ($\text{sSFR} < 0.1 \text{ Gyr}^{-1}$, $\text{SFR} < 1 \text{ M}_{\odot} \text{ yr}^{-1}$) to approximate equipartition with turbulent and CR at high star formation activity ($\text{sSFR} \gtrsim 0.1 \text{ Gyr}^{-1}$, $\text{SFR} \gtrsim 1 \text{ M}_{\odot} \text{ yr}^{-1}$).
- Varying the initial magnetisation and the seeding channel in a single Milky-Way like NUT galaxy suggests that the B -SFR slope is controlled by the dynamo's saturation state. Strong magnetic seeds ($B_0 = 10^{-10} \text{ G}$, $B_0 = 10^{-11} \text{ G}$) saturate

early and yield very shallow scalings with SFR/sSFR ($\alpha \sim 0\text{--}0.1$), whereas supernova magnetic injection (MBinj) reproduces the canonical $\alpha \simeq 0.3$ with realistic normalisation. Extremely weak seeds ($B_0 = 10^{-20} \text{ G}$) produce steep apparent slopes ($\alpha \simeq 0.5$) but remain at negligible absolute field strengths ($B \lesssim 10^{-14} \text{ G}$) for simulations with resolution of $\sim 1\text{--}10 \text{ pc}$. Thus, the injection channel sets the time to saturation, whereas the normalisation is determined by the saturation balance with turbulence. Once SN-driven turbulence maintains a saturated small-scale dynamo, a near-universal B –star formation relation emerges.

Our results emphasise that magnetic fields are dynamically important agents in shaping the structure and evolution of galaxies. Their tight correlation with star formation activity across mass, phase, and environment demonstrates that magnetism is intimately linked to supernova-driven turbulence and feedback. Magnetic energy becomes dynamically relevant, often approaching equipartition with turbulent and cosmic-ray components, for systems with ongoing star formation ($\text{sSFR} \gtrsim 0.1 \text{ Gyr}^{-1}$). In the neutral interstellar medium, both the CNM and WNM exhibit this coupling, highlighting the role of magnetic pressure in regulating cloud support and disk stability.

Recent ALMA FIR polarimetric observations of gravitationally lensed dusty star-forming galaxies at $z = 2.6$ (9io9) and $z = 5.6$ (SPT0346–52) reveal kpc-scale ordered magnetic fields, with star formation rates of $\gtrsim 10^3 \text{ M}_\odot \text{ yr}^{-1}$ and inferred field strengths of $B \lesssim 514 \text{ } \mu\text{G}$ and $\lesssim 450 \text{ } \mu\text{G}$, respectively (Geach et al., 2023; Chen et al., 2024). Under these extreme conditions, magnetic pressure and tension are likely to play a direct role in regulating star formation and shaping the dynamics of the ISM from the very early stages of galaxy formation.

The qualitative agreement between these recent high-redshift observations and the regular magnetic field morphology in our simulations suggests that signatures of large-scale magnetic ordering emerge rapidly even in highly star-forming systems, where the magnetic energy budget is still dominated by small-scale, turbulence-driven field components.

More broadly, these findings underline the importance of including multi-phase ISM physics and magnetic fields in cosmological galaxy-formation simulations, especially as the resolution in these models reaches into the sub-100 pc regime. Such models, coupled with realistic cosmic-ray transport and radiative-transfer treatments, will enable a more physically complete picture of how magnetic energy builds up and interacts with the multiphase gas. Progress on this front will require synergy with multi-wavelength polarimetric observations, spanning from the far-infrared (like the mission concept Probe far-infrared Mission for Astrophysics PRIMA, Glenn et al., 2025) to the radio:

FIR dust-polarisation tracing the dense, small-scale field structure of molecular clouds, and radio synchrotron and Faraday-rotation diagnostics probing the diffuse, large-scale magnetised halos.

Appendix A5: Simulated Maps

Figure 5.9 presents the edge-on magnetic field strength maps of the simulated galaxies used in our analysis, with the measurement region indicated by the red contours. For completeness, the corresponding face-on maps are shown in Figure 5.10, where the measurement region is defined as a circular aperture with radius set by the semi-major axis of the edge-on disk region. The B field morphology is also shown on both figures through white streamlines calculated using the density-weighted magnetic field for the entire column displayed along the line-of-sight.

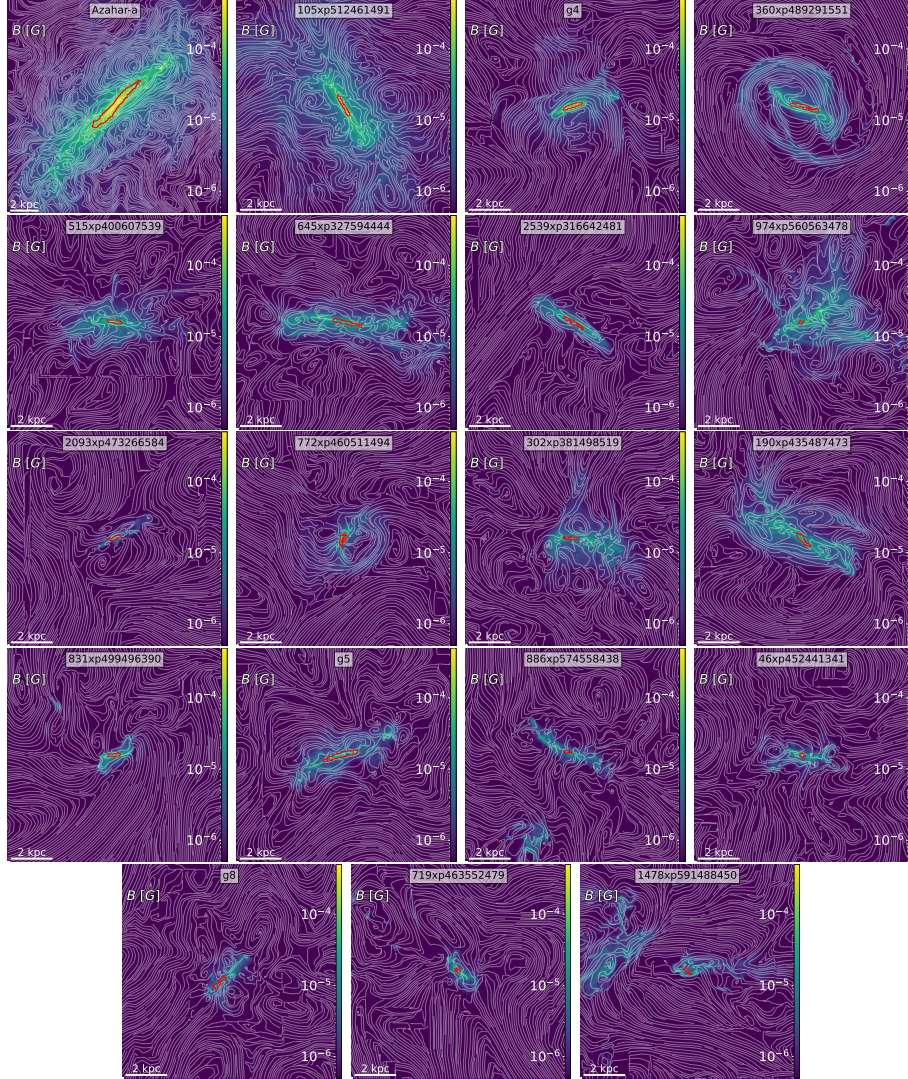


Figure 5.9. Magnetic field strength maps of the simulated galaxies shown face-on. White streamlines trace the projected magnetic field orientation, while the red contours delineate the region of the galactic disk used in the analysis.

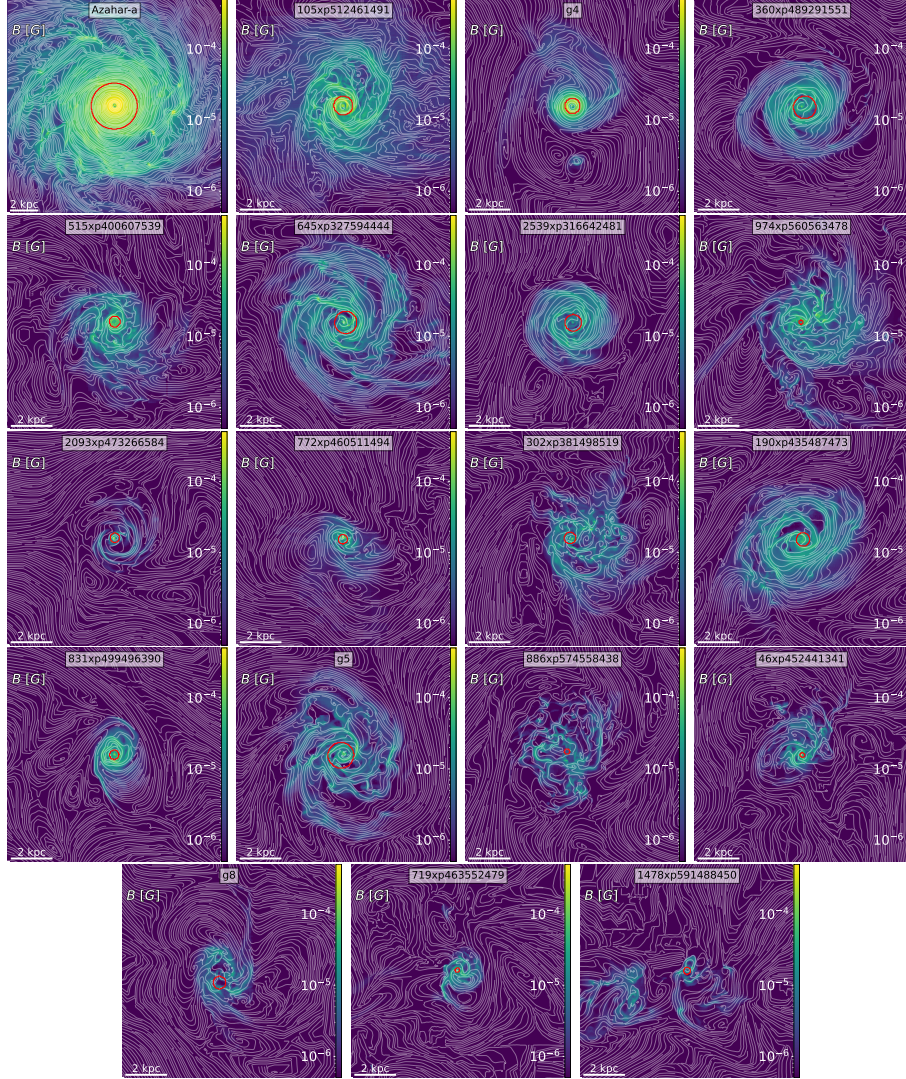


Figure 5.10. Magnetic field strength maps of the simulated galaxies shown face-on. White streamlines trace the projected magnetic field orientation. The red circles indicate the measurement apertures, defined for each galaxy as circular regions with radius equal to the semi-major axis of the disk region used in the corresponding edge-on projection shown in Figure 5.9

Appendix B5: Tables

In this section we summarise the properties of the simulated and observed samples used throughout the paper. Table 5.1 lists, for each simulated galaxy, the stellar mass M_* , the star formation rate averaged over the past 100 Myr ($\text{SFR}_{100 \text{ Myr}}$), the corresponding specific SFR ($\text{sSFR}_{100 \text{ Myr}}$), and the star formation surface density Σ_{SFR} measured over the aperture adopted for the magnetic field estimates. Table 5.2 reports the median total magnetic field strength in the disk for the full neutral gas, and separately for the cold (CNM) and warm (WNM) phases, with IQR percentile ranges indicating the scatter. Table 5.3 compiles the mass-specific magnetic, thermal, and turbulent energies (μ_{mag} , μ_{th} , μ_{turb} ; in erg g^{-1}) for the same regions and phases, enabling a direct comparison of energy budgets across the sample. For reference, Table 5.4 presents the observational compilation used for comparison with observations. It shows SFRs (with tracer noted), total magnetic field strengths, inclinations, stellar masses, sSFRs and Σ_{SFR} , where duplicate entries correspond to distinct regions within a galaxy.

Galaxy	Stellar mass [$M_{\odot}$]	$\text{SFR}_{100 \text{ Myr}}$ [$M_{\odot} \text{ yr}^{-1}$]	$\text{sSFR}_{100 \text{ Myr}}$ [Gyr^{-1}]	Σ_{SFR} [$M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$]
Azahar-a	2.07×10^{10}	6.02×10^0	2.9×10^{-1}	7.35×10^{-1}
105xp512461491	3.28×10^9	9.91×10^{-1}	3.02×10^{-1}	1.55×10^0
g4	2.4×10^9	3.25×10^{-1}	1.35×10^{-1}	7.87×10^{-1}
360xp489291551	1.28×10^9	6.48×10^{-2}	5.08×10^{-2}	7.08×10^{-2}
515xp400607539	1.19×10^9	8.11×10^{-2}	6.82×10^{-2}	3.83×10^{-1}
645xp327594444	1.12×10^9	2.12×10^{-1}	1.9×10^{-1}	2.39×10^{-1}
2539xp316642481	1.05×10^9	2.16×10^{-2}	2.06×10^{-2}	4.35×10^{-2}
974xp560563478	1.04×10^9	4.89×10^{-2}	4.71×10^{-2}	1.53×10^0
2093xp473266584	9.14×10^8	6.97×10^{-2}	7.63×10^{-2}	4.32×10^{-1}
772xp460511494	8.61×10^8	2.45×10^{-1}	2.85×10^{-1}	1.59×10^0
302xp381498519	7.82×10^8	6.64×10^{-2}	8.5×10^{-2}	2.8×10^{-1}
190xp435487473	7.42×10^8	1.67×10^{-2}	2.25×10^{-2}	5.16×10^{-2}
831xp499496390	5.64×10^8	6.44×10^{-2}	1.14×10^{-1}	4.08×10^{-1}
g5	4.82×10^8	4.1×10^{-1}	8.51×10^{-1}	3.45×10^{-1}
886xp574558438	4.43×10^8	1.34×10^{-2}	3.04×10^{-2}	2.59×10^{-1}
46xp452441341	3.54×10^8	2.73×10^{-2}	7.72×10^{-2}	7.31×10^{-1}
g8	3.03×10^8	1.1×10^{-2}	3.63×10^{-2}	3.95×10^{-2}
719xp463552479	2.64×10^8	1.22×10^{-3}	4.63×10^{-3}	3.59×10^{-2}
1478xp591488450	2.41×10^8	1.22×10^{-3}	5.07×10^{-3}	1.5×10^{-2}

Table 5.1. Unique galaxy ID (first column), stellar mass M_* (second column), SFR integrated over the last 100 Myr (third column), specific SFR (fourth column)

Galaxy	B [G]	B_{CNM} [G]	B_{WNM} [G]
Azahar-a	$1.5^{+0.55}_{-0.36} \times 10^{-4}$	$1.41^{+0.56}_{-0.34} \times 10^{-4}$	$1.54^{+0.5}_{-0.33} \times 10^{-4}$
105xp512461491	$9.33^{+1.9}_{-1.25} \times 10^{-5}$	$8.85^{+1.56}_{-1.56} \times 10^{-5}$	$9.5^{+2.12}_{-1.78} \times 10^{-5}$
g4	$1.15^{+0.3}_{-0.16} \times 10^{-4}$	$1.28^{+0.2}_{-0.32} \times 10^{-4}$	$8.39^{+2.11}_{-3.13} \times 10^{-5}$
360xp489291551	$2.52^{+0.69}_{-0.58} \times 10^{-5}$	$2.68^{+0.73}_{-0.6} \times 10^{-5}$	$1.84^{+0.62}_{-0.5} \times 10^{-5}$
515xp400607539	$5.41^{+1.02}_{-0.89} \times 10^{-5}$	$5.99^{+0.97}_{-1.07} \times 10^{-5}$	$5.14^{+1.46}_{-1.51} \times 10^{-5}$
645xp327594444	$3.09^{+0.75}_{-0.44} \times 10^{-5}$	$3.41^{+0.74}_{-0.51} \times 10^{-5}$	$2.66^{+0.75}_{-0.59} \times 10^{-5}$
2539xp316642481	$1.5^{+0.77}_{-0.22} \times 10^{-5}$	$1.52^{+1.04}_{-0.23} \times 10^{-5}$	$1.44^{+0.44}_{-0.24} \times 10^{-5}$
974xp560563478	$4^{+1.16}_{-1.37} \times 10^{-5}$	$4.23^{+0.93}_{-1.75} \times 10^{-5}$	$2.96^{+1.52}_{-0.65} \times 10^{-5}$
2093xp473266584	$9.6^{+4.3}_{-1.72} \times 10^{-6}$	$1.08^{+0.33}_{-0.24} \times 10^{-5}$	$5.21^{+4.88}_{-2.54} \times 10^{-6}$
772xp460511494	$2.91^{+1.66}_{-0.65} \times 10^{-5}$	$2.62^{+1.12}_{-0.71} \times 10^{-5}$	$2.53^{+2.06}_{-0.86} \times 10^{-5}$
302xp381498519	$1.57^{+0.68}_{-0.37} \times 10^{-5}$	$1.81^{+0.58}_{-0.51} \times 10^{-5}$	$1.47^{+0.45}_{-0.56} \times 10^{-5}$
190xp435487473	$3.15^{+0.86}_{-0.85} \times 10^{-5}$	$3.31^{+0.97}_{-0.97} \times 10^{-5}$	$2.24^{+0.9}_{-0.59} \times 10^{-5}$
831xp499496390	$4.41^{+0.92}_{-0.76} \times 10^{-5}$	$4.3^{+0.68}_{-0.76} \times 10^{-5}$	$4.25^{+1.03}_{-0.72} \times 10^{-5}$
g5	$1.88^{+0.67}_{-0.53} \times 10^{-5}$	$2.09^{+0.77}_{-0.63} \times 10^{-5}$	$1.28^{+0.52}_{-0.36} \times 10^{-5}$
886xp574558438	$1.24^{+0.58}_{-0.2} \times 10^{-5}$	$8.46^{+1.37}_{-0.67} \times 10^{-6}$	$9.91^{+2.02}_{-1.72} \times 10^{-6}$
46xp452441341	$3.55^{+1.13}_{-0.48} \times 10^{-5}$	$3.53^{+0.92}_{-0.62} \times 10^{-5}$	$3.29^{+1.07}_{-0.72} \times 10^{-5}$
g8	$1.07^{+0.25}_{-0.2} \times 10^{-5}$	$1.15^{+0.27}_{-0.22} \times 10^{-5}$	$6.63^{+2.11}_{-1.36} \times 10^{-6}$
719xp463552479	$2.71^{+1.69}_{-0.49} \times 10^{-5}$	$2.31^{+0.84}_{-0.44} \times 10^{-5}$	$2.73^{+1.86}_{-1.64} \times 10^{-5}$
1478xp591488450	$6.57^{+3.26}_{-0.89} \times 10^{-6}$	$7.68^{+3.08}_{-1.59} \times 10^{-6}$	$5.7^{+0.77}_{-2.24} \times 10^{-6}$

Table 5.2. Median magnetic field strength in the *disk* for the full gas phase, CNM, and WNM (columns 2–4).

Galaxy	Full gas			CNM			WNM		
	μ_{mag} [erg g ⁻¹]	μ_{th} [erg g ⁻¹]	μ_{turb} [erg g ⁻¹]	μ_{mag} [erg g ⁻¹]	μ_{th} [erg g ⁻¹]	μ_{turb} [erg g ⁻¹]	μ_{mag} [erg g ⁻¹]	μ_{th} [erg g ⁻¹]	μ_{turb} [erg g ⁻¹]
AZAHAR-A	3.38e+13	1.86e+12	3.17e+12	2.72e+13	8.26e+09	5.62e+12	4.15e+13	1.20e+11	1.21e+12
105xp512461491	2.89e+12	9.78e+11	2.82e+12	2.12e+12	6.23e+09	2.42e+12	3.37e+12	2.62e+11	2.41e+12
g4	3.09e+12	3.25e+11	1.33e+13	3.15e+12	1.06e+10	1.11e+13	3.74e+12	1.60e+11	1.82e+13
360xp489291551	5.71e+11	7.35e+11	1.56e+12	5.75e+11	4.43e+09	9.31e+11	6.82e+11	1.96e+11	2.53e+12
515xp400607539	1.13e+12	1.16e+12	1.62e+12	1.20e+12	5.88e+09	1.37e+12	1.24e+12	2.73e+11	1.70e+12
645xp327594444	7.28e+11	2.12e+12	4.71e+12	8.02e+11	5.02e+09	3.63e+12	7.87e+11	2.63e+11	5.50e+12
2539xp316642481	4.28e+11	3.09e+11	2.83e+12	3.80e+11	6.59e+09	2.19e+12	7.30e+11	9.72e+10	5.19e+12
974xp560563478	2.12e+11	7.37e+11	1.23e+13	1.90e+11	1.19e+10	1.46e+13	2.55e+11	1.85e+11	6.21e+12
2093xp473266584	2.94e+11	7.26e+11	6.02e+12	1.56e+11	3.11e+09	3.58e+12	4.25e+11	2.74e+11	9.53e+12
772xp460511494	6.85e+11	1.02e+12	3.93e+12	2.60e+11	2.91e+09	4.08e+12	8.05e+11	4.29e+11	3.56e+12
302xp381498519	3.30e+11	1.19e+12	1.72e+12	3.27e+11	3.62e+09	9.89e+11	3.65e+11	3.27e+11	2.44e+12
190xp435487473	4.60e+11	4.23e+11	4.30e+12	4.45e+11	8.26e+09	5.21e+12	5.26e+11	2.31e+11	2.28e+12
831xp499496390	9.31e+11	2.60e+12	4.40e+11	9.08e+11	4.90e+09	1.73e+11	9.04e+11	2.57e+11	5.46e+11
g5	3.98e+11	1.02e+12	3.75e+11	4.18e+11	4.81e+09	1.54e+11	3.72e+11	2.80e+11	4.30e+11
886xp574558438	2.11e+11	1.39e+12	5.78e+11	8.39e+10	3.81e+09	2.45e+11	9.39e+10	4.71e+11	5.11e+11
46xp452441341	3.86e+11	7.84e+11	3.58e+12	4.68e+11	6.69e+09	3.22e+12	3.62e+11	3.59e+11	4.09e+12
g8	1.67e+11	1.02e+12	5.18e+11	1.48e+11	3.72e+09	2.22e+11	1.90e+11	4.78e+11	5.54e+11
719xp463552479	2.50e+11	1.31e+12	6.82e+11	1.35e+11	5.00e+09	3.19e+11	3.83e+11	4.13e+11	8.31e+11
1478xp591488450	1.29e+10	5.18e+11	1.29e+12	1.20e+10	1.04e+10	1.29e+12	1.51e+10	1.68e+11	1.44e+12

Table 5.3. Mass-specific magnetic (μ_{mag}), thermal (μ_{th}), and turbulent (μ_{turb}) energies (in erg g⁻¹) for each galaxy, measured in the disk region.

CHAPTER 5. ANALYSIS OF AZAHAR SIMULATED GALAXIES AND COMPARISON WITH OBSERVATIONS

Galaxy	SFR [$M_{\odot} \text{ yr}^{-1}$]	B [μG]	Inclination [$^{\circ}$]	$\log M_{\star}$ [$M_{\odot}$]	sSFR [Gyr^{-1}]	Σ_{SFR} [$M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$]
M 82 [*]	$1.30 \times 10^{1 \text{ a}}$	305	81 ^a	10.01 ^a	1.27	—
NGC 253	3.00 ^q	186	78 ^b	10.47 ^a	0.10	—
NGC 2146	$2.00 \times 10^{1 \text{ r}}$	354	63 ^c	10.72 ^a	0.38	—
Equipartition B field from Beck et al., 2019						
M 31	$3.90 \times 10^{-1 \text{ b}}$	7.2	77 ^d	10.73 ^a	0.01	4.97×10^{-4}
M 33	$3.20 \times 10^{-1 \text{ b}}$	8.15	52 ^e	9.42 ^a	0.12	4.08×10^{-3}
M 51	2.70 ^c	15.5	22 ^f	10.47 ^b	0.09	1.66×10^{-2}
M 81	$5.40 \times 10^{-1 \text{ b}}$	7.2	59 ^g	10.68 ^a	0.01	1.20×10^{-3}
M 83	4.17 ^b	17.5	24 ^h	10.41 ^a	0.16	9.23×10^{-3}
NGC 253	4.90 ^b	15.0	78 ^b	10.47 ^a	0.17	3.47×10^{-2}
NGC 1097	5.01 ^b	13.0	48.6 ⁱ	10.72 ^a	0.10	6.38×10^{-2}
NGC 1365	$1.41 \times 10^{1 \text{ b}}$	12.0	40 ^j	10.75 ^a	0.25	2.03×10^{-2}
NGC 4254	5.01 ^b	17.5	42 ^k	10.52 ^a	0.15	3.07×10^{-2}
NGC 4449	$4.30 \times 10^{-1 \text{ b}}$	13.5	56.2 ^l	9.03 ^a	0.40	1.52×10^{-2}
NGC 6946	6.17 ^b	16.0	38 ^m	10.50 ^a	0.20	2.23×10^{-2}
IC 342	1.91 ^b	13.0	31 ⁿ	9.81 ^a	0.30	1.99×10^{-3}
Equipartition B field from Lacki & Beck, 2013						
M 82	7.08 ^b	240	81 ^a	10.01 ^a	0.69	3.60×10^1
NGC 253	4.90 ^b	230	78 ^b	10.47 ^a	0.17	6.94×10^1
NGC 4945	1.45 ^b	130	75 ^o	10.14 ^a	0.10	1.58×10^0
NGC 1068	$3.24 \times 10^{1 \text{ b}}$	72	40 ^p	10.71 ^a	0.63	1.14×10^0
IC 342	1.91 ^b	110	31 ⁿ	9.81 ^a	0.30	1.20×10^0
NGC 2146	$2.51 \times 10^{1 \text{ b}}$	190	63 ^c	10.72 ^a	0.48	2.96×10^1
NGC 3690	$1.55 \times 10^{2 \text{ b}}$	130	—	11.04 ^a	1.41	8.14×10^0
NGC 1808	7.94 ^b	110	57 ^z	10.29 ^a	0.41	2.38×10^0
NGC 3079	7.41 ^b	350	84 ^{aa}	10.89 ^a	0.10	6.52×10^1
Arp 220 West	$1.10 \times 10^{2 \text{ d}}$	750	$> 52^{\text{q}}$	9.30 ^d	55.0	3.50×10^3
Arp 220 East	$8.10 \times 10^{1 \text{ d}}$	720	31 ^r	9.30 ^d	40.5	2.58×10^3
Arp 193	$8.00 \times 10^{1 \text{ l}}$	550	—	10.45 ^e	2.84	9.94×10^2
Mrk 273	$1.39 \times 10^{2 \text{ k}}$	770	78 ^s	10.84 ^e	2.01	1.73×10^3
Equipartition B field from Chyży et al., 2011						
IC 1613	$2.82 \times 10^{-3 \text{ b}}$	2.8	58 ^t	8.03 ^a	0.03	8.51×10^{-5}
NGC 6822	$1.40 \times 10^{-2 \text{ e}}$	4.0	—	8.00 ^c	0.14	1.01×10^{-3}
IC 10	$5.00 \times 10^{-2 \text{ f}}$	9.7	—	7.93 ^c	0.11	1.08×10^{-2}
LMC	$2.00 \times 10^{-1 \text{ g}}$	4.3	35.8 ^u	9.18 ^c	0.13	6.82×10^{-3}
SMC	$5.00 \times 10^{-2 \text{ h}}$	3.2	—	8.66 ^c	0.58	1.18×10^{-4}
NGC 4449	$4.27 \times 10^{-1 \text{ b}}$	9.3	56.2 ^l	9.03 ^a	2.34	1.11×10^{-2}
NGC 1569	$9.55 \times 10^{-1 \text{ b}}$	14	63.2 ^v	8.61 ^a	0.40	2.76×10^{-1}
Aquarius	$1.41 \times 10^{-4 \text{ n}}$	< 4.5	—	6.02 ^a	0.14	2.46×10^{-4}
GR 8	$2.40 \times 10^{-3 \text{ m}}$	< 3.6	—	6.81 ^c	0.37	1.70×10^{-3}
WLM	$3.47 \times 10^{-3 \text{ b}}$	< 3.9	74 ^w	7.31 ^a	0.17	3.34×10^{-4}
LGS 3	$6.00 \times 10^{-6 \text{ p}}$	< 4.0	—	5.98 ^c	0.01	1.47×10^{-5}
SagDIG	$9.00 \times 10^{-4 \text{ o}}$	< 4.1	—	6.26 ^f	0.50	5.10×10^{-4}
Sextans A	$6.61 \times 10^{-3 \text{ b}}$	< 3.1	—	8.04 ^a	0.06	5.01×10^{-4}
Sextans B	$1.91 \times 10^{-3 \text{ b}}$	< 2.8	—	7.37 ^a	0.08	2.18×10^{-4}
Leo A	$2.95 \times 10^{-4 \text{ b}}$	< 4.4	—	6.45 ^a	0.10	1.44×10^{-4}
Pegasus	$6.17 \times 10^{-4 \text{ i}}$	< 3.7	—	6.82 ^c	0.09	2.96×10^{-4}
Equipartition B field from CHANGES survey						
NGC 5775	5.28 ^j	13 ^e	85.8 ^x	10.47 ^g	0.26	9.41×10^{-3}

Continued on next page

Galaxy	SFR [$M_{\odot} \text{ yr}^{-1}$]	B [μG]	Inclination [$^{\circ}$]	$\log M_{\star}$ [$M_{\odot}$]	sSFR [Gyr^{-1}]	Σ_{SFR} [$M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$]
NGC 4217	1.50 ^j	9 ^f	89 ^{ab}	10.52 ^g	0.046	3.60×10^{-3}
NGC 4666	7.30 ^j	12.3 ^g	85 ^{ac}	10.53 ^g	0.21	8.90×10^{-3}
NGC 4631	1.33 ^j	9 ^h	89 ^y	10.05 ^g	0.12	3.10×10^{-3}

Table 5.4. Star formation rates (SFRs) and total magnetic field strengths for the galaxy sample. Duplicate entries indicate different regions.

Notes. SFR tracers used: FUV+WISE4 (hybrid, ~ 100 Myr), UV+IR (hybrid), GALEX FUV (~ 100 Myr), CMD-SFH (resolved stars), FIR (10–100 Myr), IR/TIR (8–1000 μm), radio 1.4 GHz (non-thermal, ~ 100 Myr). Magnetic field strengths are synchrotron equipartition values. Inclinations are in degrees; “—” = not available/meaningful.

SFR methods by superscript: ^a (Förster Schreiber et al., 2003) IR/TIR (8–1000 μm); ^b (Leroy et al., 2019) FUV+WISE4 hybrid; ^c (Eufrasio et al., 2017) UV+IR hybrid; ^d (Varenius et al., 2016) radio 1.4 GHz; ^e (Efremova et al., 2011) GALEX FUV; ^f (Yin et al., 2010) IR/TIR; ^g (Harris & Zaritsky, 2009) CMD-based SFH (HST); ^h (Wilke et al., 2004) FIR; ⁱ (Hunter et al., 2012) GALEX FUV; ^j (Wiegert et al., 2015) FUV+WISE4 hybrid; ^k (Cicone et al., 2014) IR/TIR; ^l (Modica et al., 2012) Radio+IR composite; ^m (Ott et al., 2012) GALEX FUV; ⁿ (Leroy et al., 2021) FUV+WISE4 hybrid; ^o (Tang et al., 2016) CMD-based SFH (HST); ^p (Miller et al., 2001) CMD-based SFH (HST/WFPC2); ^q (Bolatto et al., 2013b) IR/TIR; ^r (Gorski et al., 2018) IR/TIR.

B_{tot} superscripts: ^a (Lopez-Rodriguez, 2023); ^b (Beck et al., 2019); ^c (Lacki & Beck, 2013); ^d (Chyży et al., 2011); ^e (Heald et al., 2022); ^f (Stein et al., 2020); ^g (Stein et al., 2019); ^h (Mora-Partiarroyo et al., 2019).

Inclination superscripts: ^a (Achtermann & Lacy, 1995); ^b (Pence, 1980); ^c (Della Ceca et al., 1999); ^d (McConnachie et al., 2005); ^e (Kam et al., 2015); ^f (Colombo et al., 2014); ^g (Karachentsev et al., 2013); ^h (Tilanus & Allen, 1993); ⁱ (Lang et al., 2020); ^j (Jorsater & van Moorsel, 1995); ^k (Phookun et al., 1993); ^l (Bajaja et al., 1994); ^m (Boomsma et al., 2008); ⁿ (Crosthwaite et al., 2000); ^o (Henkel et al., 2018); ^p (Schinnerer et al., 2000); ^q (Sakamoto et al., 2021); ^r (Scoville et al., 2015); ^s (Schmelz et al., 1987); ^t (Lake & Skillman, 1989); ^u (Olsen & Salyk, 2002); ^v (Sánchez-Cruces et al., 2022); ^w (Read et al., 2016); ^x (Irwin, 1994); ^y (Mora-Partiarroyo et al., 2019); ^z (Dahlem et al., 1990); ^{aa} (Israel et al., 1998); ^{ab} (Stein et al., 2020); ^{ac} (Stein et al., 2019).

$\log M_{\star}$ superscripts: ^a (Leroy et al., 2021); ^b (Wei et al., 2021); ^c (McConnachie, 2012); ^d (Sakamoto et al., 1999); ^e (U et al., 2012); ^f (Kirby et al., 2017); ^g (Leroy et al., 2019).

Appendix C5: Magnetic fields versus star formation for face-on simulated galaxies

In this section, we assess the impact of projection effects on the magnetic field–star formation relation by repeating our measurements in face-on projections of the simulated AZAHAR galaxies (shown in Figure 5.10). This test is designed to directly evaluate whether the relations inferred from the edge-on analysis depend on galaxy inclination.

For each galaxy, the measurement region in the face-on view is defined as a circular aperture whose radius is set equal to the semi-major axis of the disk region used in the corresponding edge-on projection, as illustrated in Figure 5.10. This choice ensures that the same physical extent of the star-forming disk is probed in both orientations, allowing for a consistent comparison between face-on and edge-on measurements while avoiding inclination-dependent biases in the sampled area.

The relationship of magnetic field strength with star formation is shown in Figure 5.11. We find:

$$B \propto \text{SFR}^\alpha, \quad \alpha = 0.35 \pm 0.10.$$

Within uncertainties, the slope is fully consistent with those obtained for the edge-on projections. This indicates that the inferred magnetic field–star formation relations in the AZAHAR galaxies are not significantly affected by projection effects, and the magnetic field scaling with star formation is largely independent of galaxy inclination.

We emphasize that the magnetic field strengths used in this analysis are measured directly from the intrinsic magnetic field in the simulations. In contrast, observational estimates are typically inferred indirectly and may be affected by additional systematics such as line-of-sight integration, cosmic-ray electron distributions, and radiative transfer effects (e.g. [Dacunha et al., 2025](#)).

We find that face-on projections exhibit a modestly increased scatter with respect to the edge-on case, which further improves the agreement between the simulated relations and the observational samples spanning a range of inclinations.

We interpret the increased scatter observed in the face-on projections as a consequence of the heterogeneous spatial distribution of star formation within the disk. When galaxies are viewed face-on, the star formation rate surface density appears more clumpy and spatially intermittent. In this configuration, different galaxies with similar star formation rates within the selected aperture can exhibit different degrees of star formation clustering. Such large local star formation activity variations will lead to significantly different local levels of turbulence and magnetic amplification across the spatial region, and therefore to a larger scatter. In contrast, edge-on projections collapse one of the

large disk dimensions along the line of sight, averaging over differently star-forming and magnetised. This, in turn, leads to tighter correlations. The increased scatter in the face-on case therefore reflects projection-driven differences in how spatial variations within the star-forming disk are sampled, rather than a change in the underlying physical coupling between magnetic fields and star formation.

To illustrate this, Fig. 5.12 compares the Σ_{SFR} maps of two representative AZAHAR galaxies in edge-on and face-on projections, highlighting the increased clumpiness of star formation in the face-on view.

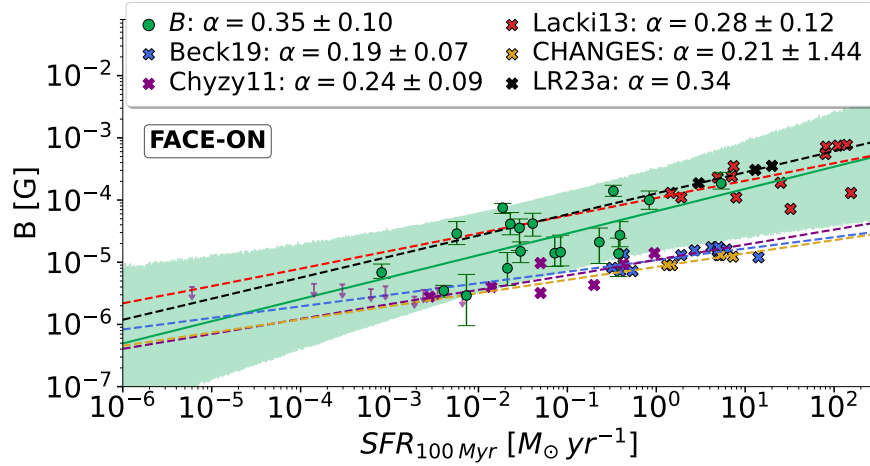


Figure 5.11. Magnetic field strength as a function of integrated SFR over the last 100 Myrs. Each panel shows the median magnetic field strength B measured in face-on projections of the simulated AZAHAR galaxy sample (green solid circles). The magnetic field is computed within a circular aperture whose radius is set equal to the semi-major axis of the disk region used for the corresponding edge-on projection (measured as described in Section 5.1.1). Error bars show IQR range. The solid green line shows the best fit, and the shaded region indicates the 95% prediction interval, with their fitted slopes and the standard error reported in the legends. Samples of observed galaxies taken from the literature and their best-fit relations (dashed lines), are overlaid with different color crosses: red (Lacki & Beck, 2013), black (Lopez-Rodriguez, 2023), purple (Chyży et al., 2011), navy blue (Beck et al., 2019), and goldenrod (Heald et al., 2022; Stein et al., 2020, 2019; Mora-Partiarroyo et al., 2019, CHANGES survey). Their respective best-fit relations are shown as dashed lines. Upper limits from Chyży et al. (2011) are shown as downward arrows, and are excluded from the fits.

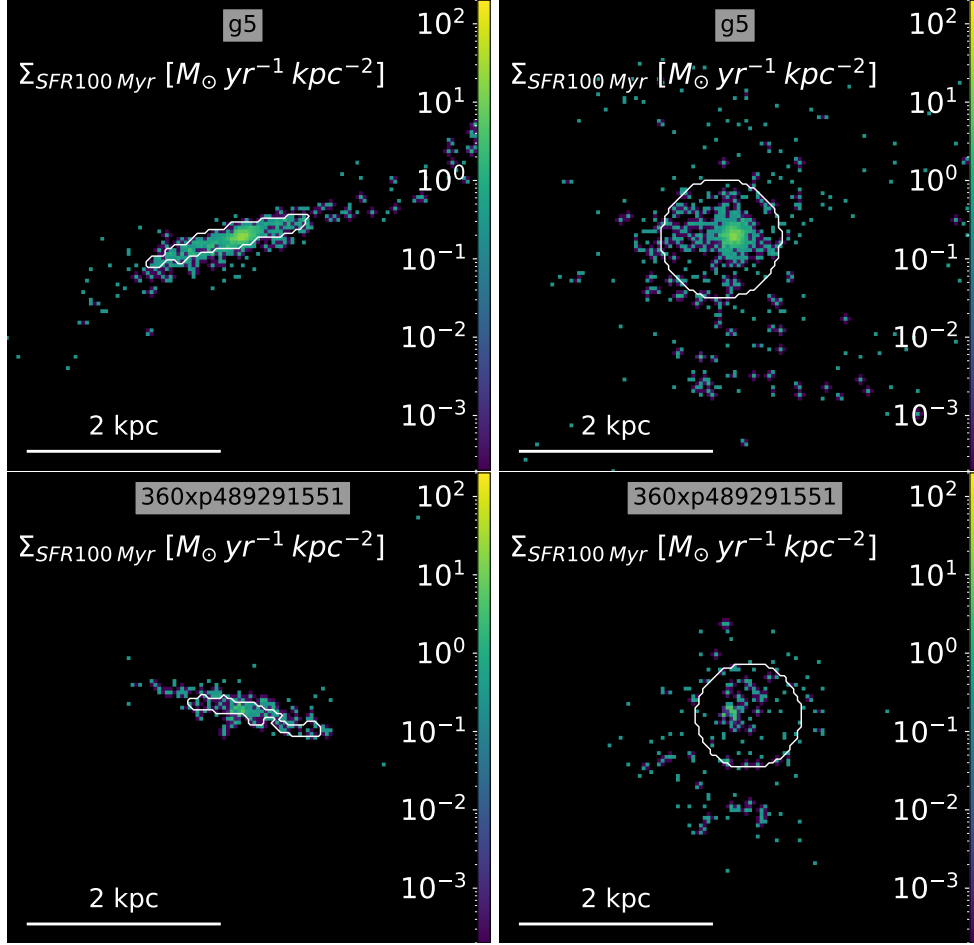


Figure 5.12. Comparison of star formation rate surface density maps for galaxies g5 and 360xp489291551. Each row shows the same galaxy viewed in edge-on (left) and face-on (right) projections.

6

Conclusions and Future Perspectives

In this thesis we investigated how magnetic fields influence the interstellar medium and regulate star formation using two complementary approaches. First, we presented parsec-scale ALMA polarimetric observations of the nuclear starburst in NGC 253, resolving the magnetic-field morphology and its coupling to feedback in a dense environment. Second, we analysed a suite of cosmological magnetohydrodynamical simulations (AZAHAR) to quantify how magnetic energy scales with star formation and other ISM properties across spiral galaxies. Together, these observational and theoretical perspectives address a central question: how magnetic fields in galaxies are seeded, amplified, and structured, how they achieve near equipartition with other interstellar medium (ISM) energy components, and how they influence the cycle of star formation and outflows.

This chapter synthesises the main results and outlines a concrete path forward. We first summarise the observational and simulation findings and show how they converge on a unified physical picture; we then identify the key open questions that emerge; finally, we describe future work that extends both fronts.

Section 6.1 reviews the achieved results: the ALMA constraints on magnetic-field morphology, depolarisation, and band-dependent emission mechanisms in NGC 253, and the AZAHAR-based scalings linking the magnetic field strength B to star formation and ISM energetics across spiral galaxies. Section 6.2 lists the outstanding questions, both observational (e.g. dust vs. synchrotron depolarisation, phase continuity of the field, frequency dependence of PF) and theoretical (e.g. magnetic amplification and energetics in winds).

Section 6.3 presents future directions. It outlines a joint ALMA+VLA polarimetric programme that fills the spectral gap between radio and submm at matched ~ 8 pc resolution, and a simulation effort to quantify magnetic amplification and energy transport in galactic outflows, directly comparable to the new data. The chapter closes with a brief Final remarks in Section 6.4 on the broader implications for galactic magnetism and galaxy evolution.

6.1 Summary of achieved results

6.1.1 Observations of magnetic field in the Centre of NGC 253

Using ALMA polarimetric observations in Bands 7 (345 GHz, ~ 5 pc) and 4 (145 GHz, ~ 25 pc), we mapped the magnetic field structure in the central 200 pc of NGC 253, a nearby starburst galaxy. Advanced imaging techniques, properly handling noise, and SED fitting revealed the following:

- Band 7 emission is dominated by thermal dust, while Band 4 includes comparable contributions from dust, synchrotron, and free-free.
- The polarisation fraction averages 1% but drops to 0.3% near super-star clusters and dense regions, likely due to reduced dust grain alignment or tangled magnetic fields.
- At a matched 25 pc resolution, Bands 4 and 7 show consistent magnetic field orientations, suggesting a unified field structure across dense molecular and diffuse ionized gas phases.
- The magnetic field aligns with the base of the biconical outflow, indicating that magnetic tension helps shaping and possibly collimating the outflow.
- The polarisation fraction anti-correlates with gas column density and polarisation angle dispersion, consistent with beam averaging or line-of-sight field tangling.

These findings show that ordered magnetic fields couple feedback to the multiphase ISM in the prototypical starburst NGC 253, and are reported in [Belfiori et al., 2025](#).

6.1.2 Simulations of Magnetism and Star Formation in Galaxies

We analyzed 19 spiral galaxies from the AZAHAR cosmological MHD simulations. These simulations evolve gas, stars, magnetic fields, cosmic rays, and radiative transfer self-consistently, allowing us to study magnetic amplification without assuming equipartition (equal magnetic and turbulent energies). Key results include:

- Simulated galaxies follow a universal magnetic field–star formation relation, $B \propto \text{SFR}^{0.2-0.3}$, matching observational trends.
- The magnetic field strength scales with surface star formation rate as $B \propto \Sigma_{\text{SFR}}^{1/3}$, consistent with a supernova-driven, turbulence-regulated small-scale dynamo.

- Magnetic energy approaches equipartition with turbulent energy in galaxies with $\text{SFR} \gtrsim 1 M_{\odot} \text{ yr}^{-1}$, indicating dynamic importance.
- The B –SFR relation holds across cold and warm neutral media (CNM, WNM), suggesting a shared amplification mechanism.
- The initial magnetic seed and injection mechanism (e.g., supernova-driven vs. primordial) affect the B –SFR slope: strong seeds saturate early with flat slopes ($\alpha \simeq 0.1$), supernova injection yields $\alpha \simeq 0.3$, and weak seeds produce steeper slopes ($\alpha \simeq 0.5$) but weaker fields.

These results show that magnetic fields self-regulate with star formation through supernova-driven turbulence, reaching equipartition in active galaxies, and are presented in [Belfiori et al., 2026](#).

6.1.3 Linking Observations and Simulations

Both the observations of NGC 253 and the simulations of spiral galaxies converge toward a coherent physical picture. Magnetic fields in galaxies are amplified by SN-driven turbulence and become dynamically relevant once equipartition with turbulent energy is reached. This coupling produces the observed scaling between B and star formation rate, and regulates ISM structure across gas phases.

From an observational perspective, ALMA polarimetry provides direct evidence of ordered fields in dense starburst environments and of depolarisation signatures consistent with field tangling and grain-alignment variations. From a theoretical standpoint, the AZAHAR simulations quantify the expected scaling of magnetic and non-thermal energies with star formation, reproducing the empirical B –SFR/sSFR/ Σ_{SFR} relation and its phase invariance.

The two approaches are thus complementary: simulations describe the underlying energy transfer and dynamo physics, while polarisation observations constrain the morphology, coherence, and multi-phase coupling of the field. Together they indicate that magnetism is a fundamental component of star formation and feedback in galaxies.

6.2 Open Questions

Several key questions remain open on both the observational and theoretical fronts. They can be broadly grouped into two complementary domains that motivate the future directions described in Section 6.3.

Observational and polarimetric questions.

- **Origin of depolarisation in starburst nuclei.** Is the low dust polarisation near the super starclusters (SSCs) caused by reduced grain-alignment efficiency, local optical-depth effects, or geometric tangling along the line of sight?
- **Phase continuity of magnetic fields.** Do dust and synchrotron emission trace a common magnetic-field geometry, or do fields decouple between dense molecular and diffuse ionised phases? On larger scales, synchrotron polarisation observations of NGC 253 at centimetre wavelengths show an ordered magnetic field in the disk that connects smoothly to the field aligned with the nuclear outflow (Heesen et al., 2009), closely resembling the plane-of-sky field morphology inferred here from ALMA Bands 4 and 7 at matched resolution. Our results therefore suggest continuity of the magnetic-field geometry across spatial scales and emission mechanisms, but a mechanism-resolved comparison is required to test whether the same field is traced in the dense and diffuse phases.
- **Frequency dependence of polarised emission.** How does the polarisation fraction evolve from the synchrotron - to dust-dominated regimes?

Theoretical and simulation-based questions.

- **Role of magnetic fields in outflows.** Do feedback-driven winds merely advect magnetised gas, or can they further amplify magnetic energy through shear, compression, or turbulence? What fraction of the disk magnetic energy is transported into the halo, and how does this affect the maintenance of large-scale magnetisation?
- **Phase-dependent coupling and energetics.** How do magnetic, turbulent, and cosmic-ray pressures evolve within the multiphase outflow, and what determines their relative importance? Understanding this coupling is fundamental to establishing whether magnetised outflows contribute to sustaining or regenerating galactic dynamos.

Answering these questions requires a coordinated approach that combines high-resolution, multi-frequency polarimetric observations with detailed numerical experiments.

6.3 Future Work

6.3.1 Joint ALMA+VLA Polarimetry of NGC 253

To answer the first part of these open issues, an approved Cycle 12 joint ALMA+VLA programme (Project ID: 2025.1.00732.S) will provide full-polarisation observations of the NGC 253 nucleus from 3.5 to 350 GHz at $0.5''$ (~ 8 pc) resolution. This programme represents the natural continuation of the observational work presented in Chapter 3.

The new dataset will provide full-Stokes observations in ALMA Bands 1 (~ 42 GHz) and 4 (~ 145 GHz), complemented by VLA Bands S (3.5 GHz) and X (8.5 GHz), all at $0.5''$ (~ 8 pc) resolution. This angular resolution matches the existing Band 7 observations analysed in Chapter 3, enabling a direct comparison across frequencies and emission mechanisms. At all frequencies, the proposed single-pointing observations cover angular scales equal to or larger than those recovered in Band 7, ensuring complete spatial sampling of the starburst region.

The main goal of this joint programme is to complement and extend the current ALMA dataset by adding the crucial frequency range where the transition from synchrotron to dust emission occurs. By filling this spectral gap, we will obtain an unbroken polarisation spectrum that traces the interplay between non-thermal and thermal mechanisms from the radio to the submillimetre domain. This frequency coverage is essential to measure the spectral behaviour of the polarisation fraction, to determine the relative contribution of each emission component, and to assess whether the plane-of-sky magnetic-field geometry is continuous across ISM phases.

These data will allow us to study the following topics:

- **Frequency dependence of dust polarisation.** The total-intensity SED of the central region of NGC 253 (See Figure 6.1 and Section 3.7) shows that in the ALMA Band 1 and Band 4 window none of the emission mechanisms is negligible. The new ALMA (B1, B4) and VLA (S, X) data provide the required leverage to measure, at matched $0.5''$ (~ 8 pc) resolution, the spectral behaviour of both synchrotron and dust polarised emission and to isolate the dust contribution across 40–150 GHz. Existing dust-polarisation models predict a rise in $PF(\nu)$ from ~ 40 to ~ 100 GHz followed by an approximately flat trend toward higher frequencies, with differences linked to grain composition and geometry (segregated vs. homogeneous mixtures). We will test these predictions across spatial scales and environments in the starburst nucleus—an ideal laboratory given its SSCs and outflow activity.

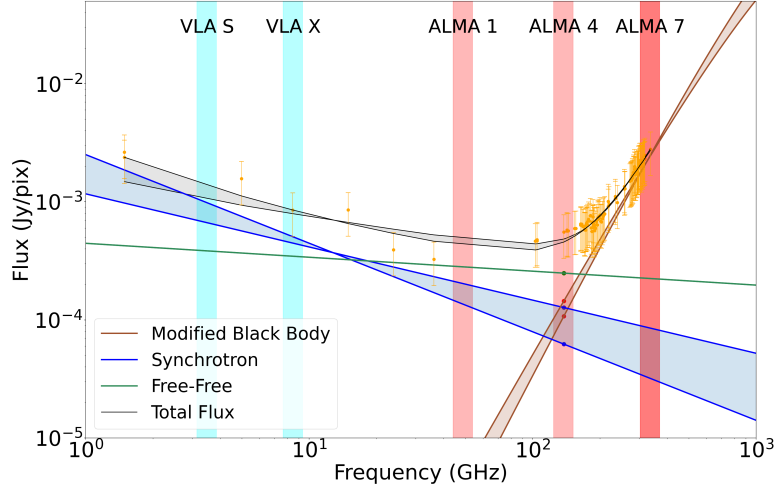


Figure 6.1. Total intensity SED decomposition of ALMA and VLA archival data targeting the mid-plane of NGC 253. The position of the existing high resolution ALMA B7 data from [Belfiori et al. \(2025\)](#) (dark red) and the new observations of ALMA (light red) and VLA (light blue) awarded through the approved joint ALMA–VLA polarimetric proposal are shown as well. Yellow points show observed measurements taken from various sources in literature (listed in Table 3.5).

- Dust and synchrotron as complementary tracers of the magnetic field.** We will compare polarisation fractions and plane-of-sky angles from dust and synchrotron at matched ~ 8 pc resolution across the full field. This constitutes the first mechanism-resolved comparison of magnetic geometry at parsec scales in an external galaxy. In our Band 4 analysis we reported a spatial coupling between the inferred B-field orientation and the base of the outflow, although Band 4 mixes dust and synchrotron. By separating the two mechanisms, we will directly assess how the magnetic field couples to the wind in different ISM phases, and whether the phase-resolved field geometries agree or systematically diverge.
- Physical drivers of depolarisation in starburst environments.** Our Band 7 maps revealed a correlation between low polarisation fraction and the locations of SSCs, suggesting that stellar feedback may contribute to dust depolarisation. With the new lower-frequency data we will test whether analogous minima occur in the synchrotron component. If they do not, the depolarisation is likely dust-specific (e.g. changes in grain populations, alignment efficiency, or optical-depth effects); if they do, geometric tangling along the line of sight and within the beam is favoured as the dominant cause.

This program will provide the first mechanism-resolved view of magnetic fields in an external galaxy at parsec scales, with implications for dust physics, cosmology, and magnetised feedback.

6.3.2 Magnetic-field tracing in dense molecular gas through the Goldreich–Kylafis effect.

In addition to continuum polarimetry, NGC 253 offers a unique opportunity to probe the magnetic field in the dense molecular phase via linearly polarised molecular-line emission arising from the Goldreich–Kylafis effect (Goldreich & Kylafis, 1981 see Section 2.2 for a description of the underlying mechanism). Owing to its exceptionally bright and spatially extended CO emission in the nuclear region (e.g. Bolatto et al., 2013b), NGC 253 represents an ideal target to search for linearly polarised molecular emission at high angular resolution.

Polarisation produced by the Goldreich–Kylafis effect traces the orientation of the magnetic field projected on the plane of the sky in molecular gas, providing a direct and independent constraint on the field geometry within star-forming clouds and dense filaments. A comparison between the magnetic-field orientation inferred from molecular-line polarisation and that derived from dust continuum polarisation would allow us to test whether both tracers probe the same underlying magnetic-field structure in the dense ISM, or whether systematic differences arise due to phase-dependent field topology, line-of-sight averaging, or local radiative and excitation conditions.

Such a comparison would therefore provide a direct observational test of magnetic-field continuity between the dust-emitting and molecular gas phases on parsec scales, and would complement the dust–synchrotron comparison discussed above by adding an explicit probe of the cold and dense star-forming component of the interstellar medium.

6.3.3 Magnetic Fields and Outflows in Simulated Galaxies

With the simulations described in this thesis we established that magnetic field amplification in galaxy disks follows a near-universal B –star formation scaling and reaches approximate equipartition with turbulence in actively star-forming systems. A natural continuation of this work is to extend the analysis beyond the disk and into the galactic outflows, in order to determine whether feedback-driven winds merely advect magnetic energy or actively participate in its amplification. This effort will provide the theoretical counterpart to the observational follow-up of NGC 253 described in Section 6.3.1, linking the disk dynamo physics revealed in the AZAHAR galaxies to the magnetised winds observed in starburst systems.

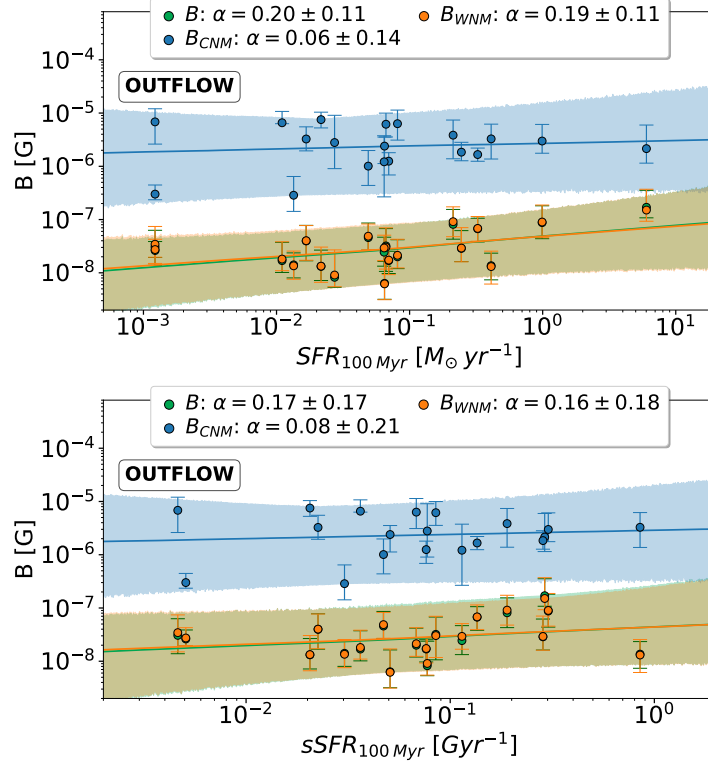


Figure 6.2. Magnetic field strength as a function of the star formation rate (top) and the specific star formation rate (bottom), both averaged over the last 100 Myr. Only the outflowing gas ($v > 50 \text{ km s}^{-1}$) outside the disk region is considered. Coloured symbols show the measurements for the full gas, CNM, and WNM phases, with corresponding best-fit relations indicated by the solid lines of matching colour. Shaded region indicates the 95% prediction interval.

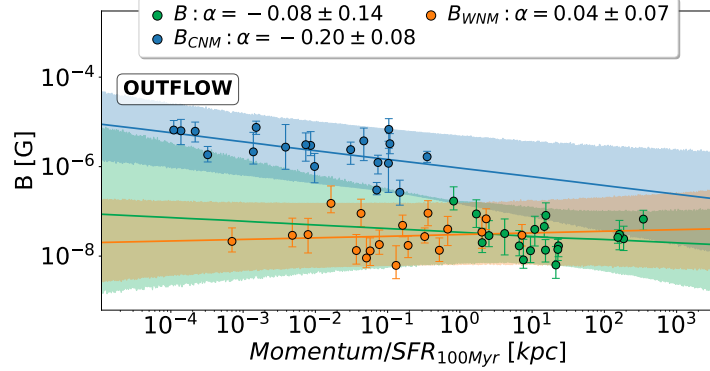


Figure 6.3. Magnetic field strength as a function of integrated momentum associated with the outflow ($v > 50 \text{ km s}^{-1}$) and computed outside the disk region for the different gas phases. Coloured symbols show the measurements for the full gas, CNM, and WNM phases, with corresponding best-fit relations indicated by the solid lines of matching colour. Shaded region indicates the 95% prediction interval.

Scientific motivation. Recent observational results for nearby starbursts, including NGC 253 and M82, show magnetic-field lines aligned with the direction of the outflow and field strengths that remain comparable to the kinetic energy density up to kiloparsec scales (Heesen et al., 2011; Lopez-Rodriguez et al., 2021). These findings suggest that winds may play an active role in transporting and possibly amplifying magnetisation. However, the physical coupling between magnetic, turbulent, and kinetic energy in outflows, and its dependence on galaxy properties, remains poorly quantified in simulations. Understanding this connection is essential to assess whether feedback-driven winds can sustain or regenerate the galactic dynamo beyond the disk.

Preliminary results with Azahar Using the Azahar simulations described in Chapter 5, we have performed a first preliminary extension of the analysis to the extraplanar gas, selecting outflowing material with $v_{\text{out}} > 50 \text{ km s}^{-1}$ outside the disk region. Figure 6.2 shows that the magnetic field in the outflow correlates positively, though more weakly than in the disk, with the galaxy star-formation rate:

$$\alpha_{\text{full}} = -0.08 \pm 0.14, \quad \alpha_{\text{WNM}} = 0.04 \pm 0.07, \quad \alpha_{\text{CNM}} = -0.20 \pm 0.08.$$

The slope reduction is consistent with geometric dilution under flux freezing as gas expands away from the plane. These patterns suggest that a saturated small-scale dynamo established in the disk is advected into the neutral wind.

We also investigated the relation between outflow magnetisation and momentum loading, defined as the total gas momentum divided by the SFR of each galaxy (see

Figure 6.3). The results do not reveal any significant correlation between momentum loading and magnetic field strength in the gas components

These preliminary results are in contrast to the clearer correlation observed between magnetic field strength and SFR described in Chapter 5, implying that magnetic field amplification is primarily linked to star formation activity within the disk, rather than being directly driven by the bulk momentum of the outflowing gas. This finding echoes the observational picture of NGC 253, where the amplified fields produced in the nuclear disk appear to be dragged into the circumgalactic medium.

Building on these initial results, future work will pursue three goals:

- **Quantify magnetic amplification in winds.** Measure scale-dependent energy transfer between kinetic and magnetic reservoirs in outflows, testing whether shear, compression, or turbulence within the wind can further amplify B , beyond simple advection.
- **Characterise phase-dependent energetics.** Extend the energy-budget analysis of the AZAHAR suite to the full multi-phase outflow (neutral, ionised, and hot components), determining how magnetic-to-turbulent ratios vary with height, temperature, and mass-loading.
- **Connect outflow geometry to dynamo evolution.** Relate magnetic-field topology and coherence length to wind morphology, comparing systems with different disk masses, SFRs, and feedback efficiencies to identify the regimes where outflows contribute to global dynamo saturation.

Methodology. The next phase of analysis will exploit the full three-dimensional outputs of the AZAHAR and NUT simulations, using tracer particles and velocity-field decomposition to isolate coherent versus turbulent components of the wind. We will compute vertical energy, magnetic helicity transport, and phase-resolved mass and momentum loading to evaluate the role of magnetic fields in shaping outflow structure. Comparisons with synthetic observables (polarisation fraction, rotation measures, and synchrotron maps) will allow a direct link to ALMA and VLA measurements of NGC 253 and other starbursts.

Expected outcomes. This study will clarify whether outflows act as sinks, conveyors, or amplifiers of galactic magnetic energy. It will quantify how magnetisation evolves from the disk into the halo, establish the conditions under which winds contribute to magnetic-field growth, and provide theoretical predictions for the magnetised outflows

now being observed in nearby galaxies. Ultimately, the results will complete the picture emerging from this thesis: a self-consistent cycle in which star formation amplifies magnetic fields through turbulence, and magnetised feedback in turn regulates star formation and transports magnetic energy into the circumgalactic medium.

6.4 Final remarks

From the dusty nucleus of NGC 253 to the cosmological disks of the AZAHAR simulations, this thesis has explored how magnetic fields emerge, evolve, and shape the life cycle of galaxies. Observations at parsec resolution have revealed that magnetic forces are not passive spectators of feedback, but active participants that thread the interstellar medium, collimate outflows, and regulate star formation in one of the nearest starbursts. In parallel, large-scale simulations have shown that the same physical principles—supernova-driven turbulence and small-scale dynamo amplification—govern the build-up of magnetism across vastly different environments.

Together, these two perspectives outline a unified picture of galactic magnetism as a self-regulated process linking stars, gas, and feedback in a common energetic framework. Magnetic fields attain equipartition wherever star formation is vigorous, imprinting order within chaos and coupling the visible and invisible components of galaxies.

Looking ahead, the synergy between high-resolution polarimetry and physics-rich simulations promises to transform our understanding of cosmic magnetism—from the dusty cores of local starbursts to the first galaxies of the early Universe. Future multi-wavelength observations, combined with cosmological MHD modelling, will turn magnetic fields from a hidden parameter into a measurable driver of galaxy evolution.

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