



Measuring Magnetic Field Strengths in Galactic Star-forming Regions via the Zeeman Effect with the SKA

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Magnetic fields thread the interstellar medium from the largest to the smallest scales and play an important role in molecular cloud evolution and star formation. Quantifying this requires measurements of the field strengths, and the most direct way to measure them is via the Zeeman effect in spectral lines. The effect is subtle for the typical field strengths expected from theory, from a few μG in diffuse molecular clouds to a few 10s of mG in dense star-forming regions, and detections are scarce. Existing measurements of magnetic field strength suggest dense clouds and cores are marginally supercritical (cannot prevent collapse, but can inhibit it), but may be biased due to small sample sizes. Zeeman effect measurements tracing different scales and densities within molecular clouds can reveal the variation of field strengths, providing critical measurements to address the question of whether star formation is primarily regulated by magnetic fields or turbulence on different scales. Observations with SKA precursors such MeerKAT and FAST are beginning to increase the number of Zeeman effect detections in nearby star-forming regions. The SKA will extend their reach to many regions within our Galaxy that are best representative of where most stars form, while zooming in on the densest star-forming regions, providing a statistical basis for the role of magnetic fields in molecular cloud evolution and star formation. We present predictions and plans for Zeeman effect observations with the SKA telescopes, demonstrating the significant advances they will provide for studies of magnetic fields in molecular clouds.

1 Introduction

Stars form in dense cores within filaments in clouds of molecular gas and dust. The contraction and collapse of gas and dust to form stars occurs over molecular cloud size scales of 10s of pc down to the sub-au scales of protostars, and spans many orders of magnitude in density. The evolution of molecular clouds and their ability to form stars is driven primarily by the interplay between gravity, magnetic fields, and turbulence. Star formation is an inefficient process: the rate of star formation within our Galaxy is much lower than would be the case if it were driven by gravity alone. Molecular clouds convert only a small fraction of their mass into stars during their lifetimes (Zuckerman and Palmer, 1974; Zuckerman and Evans, 1974; Elmegreen, 1985). The key challenges to understanding the inefficiency of star formation are determining which of the two opposing forces, magnetic fields or turbulence, is most important in regulating star formation on different size scales, whether that influence is dominant in suppressing star formation or simply slowing it down, and to what degree. Understanding the reasons why star formation is inefficient are extremely important as the star-formation rate (SFR) has consequences for our understanding of planet formation and galaxy evolution (Evans, 1999).

Understanding the extent of the influence of magnetic fields on star formation has been challenging, due to the difficulty in tracing field structure and measuring field strengths on different size scales within molecular clouds using current instrumentation (Crutcher, 2012; Han, 2017; Li, 2021; Pattle et al., 2023). To address the question of the importance of magnetic fields in regulating star formation, careful measurement of field structure and strength on the different size scales and densities within molecular clouds is required. Additionally, studies have shown that magnetic morphology can reveal structures invisible to total emission observations (Tahani et al., 2022b; Mohammed et al., 2024), the energy budgets in molecular clouds (Tahani et al., 2023), and formation and evolution of clouds (Tahani et al., 2022a; Tahani, 2022).

Field structure within molecular clouds is best traced via polarised dust emission at mm and submm wavelengths, revealing the plane-of-sky structure (Liu et al., 2022; Pattle et al., 2023). The number of maps of field structure has increased significantly in recent years, primarily due to large programs on SOFIA and in particular the JCMT (e.g., the BISTRO survey; Ward-Thompson et al., 2017; Pattle et al., 2017). Together with Planck polarisation maps, these have increased our knowledge of how field structure varies from large to small scales in different star-forming regions. Polarisation maps at sub-core scales are now emerging from ALMA observations which will add to our understanding of field variations down to the scale of protostars. Although field strength can be indirectly inferred from field structure maps via the Davis-Chandrasekhar-Fermi (DCF) method (§5.1, these estimates rely on assumptions and there are caveats which may not always be fulfilled (Heiles and Robishaw, 2009; Liu et al., 2022; Pattle et al., 2023).

The most direct measure of magnetic field strength is through observations of the Zeeman effect in spectral lines of selected atoms and molecules at radio and mm wavelengths (see reviews by Heiles et al. (1993); Crutcher and Kemball (2019)). For the typical physical conditions found throughout the bulk of a molecular cloud, the magnitude of the Zeeman effect is small, requiring very sensitive observations for its detection (see §2), and only the value of the line-of-sight (LOS) component of the field can be inferred (the exception is observations of the Zeeman effect in some maser lines of

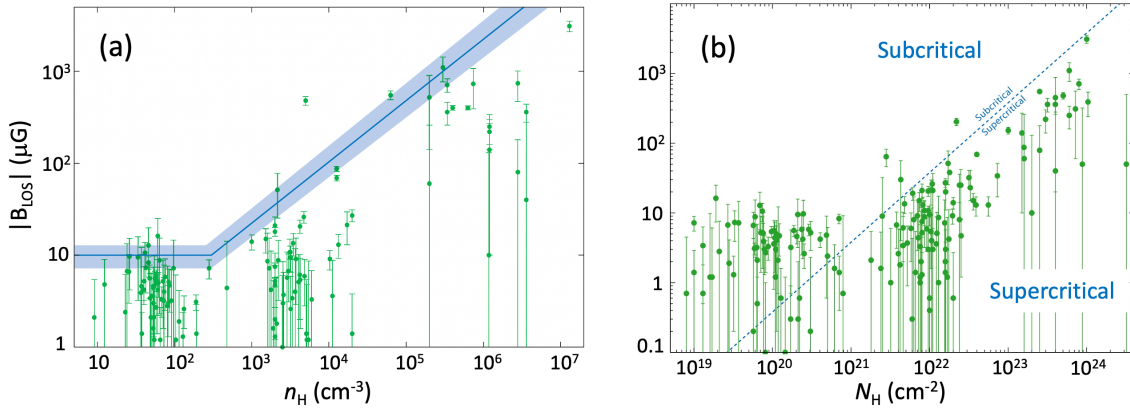


Figure 1: (a) The set of diffuse cloud and molecular cloud Zeeman effect measurements of the magnitude of the line-of-sight component B_{LOS} of the magnetic vector B and their 1σ uncertainties, plotted against n_H ($= n(\text{HI})$ or $2n(\text{H}_2)$) for HI and molecular clouds, respectively (Crutcher et al., 2010). Although Zeeman effect measurements give the direction of the line-of-sight component as well as the magnitude, only the magnitudes are plotted. The solid blue line shows the most probable maximum values for $B_{TOT}(n_H)$ determined from the plotted values of B_{LOS} by the Bayesian analysis of Crutcher et al. (2010). Also shown (plotted as light blue shading) are the ranges given by acceptable alternative model parameters to indicate the uncertainty in the model. (b) HI, OH, and CN Zeeman effect measurements of B_{LOS} versus $N_H = N_{\text{HI}} + 2N_{\text{H}_2}$. The dashed blue line is for a critical mass-to-flux ratio $(M/\Phi)_{crit} = 3.8 \times 10^{-21} N_H / B$. Measurements above this line are subcritical, those below are supercritical (see section 6). Figure adapted from Crutcher (2012).

OH, where the full field strength can be recovered - see §3.7).

As a result, the number of Zeeman effect detections remains small, even after decades of effort, due to the need for long integration times using radio telescopes with stable and well-understood polarimetric responses. However, the power of Zeeman measurements in providing the most accurate field strength measurements highlights their importance for mapping the three-dimensional (3D) structure of interstellar magnetic fields (see chapter by Tahani et al. (2026)) and for determining the energy budgets within molecular clouds. The few existing measurements of field strength suggest clouds & cores are marginally supercritical (cannot prevent collapse, but can slow the rate of star formation), but this result may be biased due to small sample sizes.

Figure 1 summarizes most of the published Zeeman effect measurements toward molecular clouds (and diffuse HI clouds). Although these plots were presented over 10 years ago, very little new observational data have been published, and therefore there is almost no new information to add to these figures. This lack of advancement highlights the difficulty in measuring the Zeeman effect with pre-SKA facilities, and the lack of desire for attempting new measurements with new SKA precursors and pathfinders (e.g., ASKAP, MeerKAT, FAST), until now. The observations are challenging and more often than not have resulted in non-detections.

Fig. 1(a) presents the Zeeman effect measurement results for a set of atomic and molecular clouds compiled by Crutcher et al. (2010), which represents most of the measurements available at that time for which an estimate of the volume density is also available (Crutcher, 2012). This plot shows clustering of data around $n \sim 10^2 \text{ cm}^{-3}$ from HI 21-cm observations, around $n \sim 10^{3.5} \text{ cm}^{-3}$ from

OH 18-cm observations, and a spread of data at higher values of n from CN 3-mm observations. Many of the measurements are upper limits (i.e., non-detections), but are included as "detections" for the Bayesian analysis performed by [Crutcher et al. \(2010\)](#), shown by the blue line (indicating the most probable value for the total field strength, B_{TOT}) and shading in the figure.

Fig. 1(b) presents B_{LOS} and N_{H} for five major Zeeman effect surveys for which both values are presented ([Crutcher, 2012](#)). This figure also plots the critical mass-to-flux ratio $(M/\Phi)_{\text{crit}}$, indicating the regions in the plot for subcritical (magnetically supported) and supercritical (magnetic field cannot prevent gravitational collapse) values (geometric corrections may move the line vertically; [Bourke et al., 2001](#)).

The analysis of the data presented in these figures suggests:

1. field strength is constant at $\sim 10 \mu\text{G}$ for $n_{\text{H}} < 300 \text{ cm}^{-3}$ (or at least does not vary strongly), which may mark the transition from diffuse to self-gravitating clouds,
2. above $n_{\text{H}} \sim 300 \text{ cm}^{-3}$, field strength increases with density as a power law $B \propto n^{\kappa}$ with index $\kappa \sim 0.65$, as expected for spherical clouds contracting (or collapsing) with flux-freezing ([Mestel, 1966](#), but see, e.g., [Mouschovias and Tassis 2010](#), for counter-arguments), but significantly different from that expected for clouds contracting via ambipolar diffusion of ~ 0.5 ([Mouschovias and Ciolek, 1999](#)),
3. most molecular clouds on all size scales are magnetically supercritical, or close to the critical mass-to-flux ratio, suggesting that while magnetic fields cannot prevent collapse, they may slow star formation.

These results are interesting but are inferred from a small number of Zeeman effect measurements overall (including upper limits), and very few actual detections of the Zeeman effect. The interpretation and analysis is also subject to debate ([Mouschovias and Tassis, 2010](#); [Jiang et al., 2020](#); [Zhao et al., 2024](#)). Filling in these figures with many more Zeeman detections, along with careful estimates of the column and number densities of the gas in which the effect is measured, is key to making progress.

2 The Zeeman Effect – Observational Considerations

The Zeeman effect and its application to the measurement of field strengths in the ISM and molecular clouds is described in detail by [Heiles et al. \(1993\)](#); [Crutcher et al. \(1993\)](#); [Robishaw \(2008\)](#); [Crutcher and Kemball \(2019\)](#); and [Robishaw and Heiles \(2021\)](#). In this section we provide a brief description of its direct applicability for observations.

Observationally, the Zeeman effect most often reveals itself as small frequency shifts, $\Delta\nu_z$, in the right and left circularly polarized (RCP and LCP, respectively) components of the spectral line with respect to the frequency in the zero field case, ν_0 . The frequency shift is given by

$$\begin{aligned} \Delta\nu_z &= \frac{g \mu_B}{h} B \\ &= \frac{Z}{2} B \end{aligned} \tag{1}$$

where g is the transition-specific Landé g -factor, μ_B is the Bohr magneton, h is Planck's constant, B the magnetic field strength. The "Zeeman splitting factor", $Z = 2g\mu_B/h$, is specific for each spectral transition and is listed in Table 1. The quantum mechanical calculation of g -factors is non-trivial, and accurate values for some transitions are still debated (§3.8).

The magnetic field is determined from the Stokes V spectrum, $V = RCP - LCP$, whereas Stokes $I = RCP + LCP$. Under most astrophysical conditions, $\Delta\nu_z \ll \Delta\nu$, where $\Delta\nu$ is the full width at half maximum of the spectral line (the exceptions are some OH masers, see §3.1), and so detecting the shift between the RCP and LCP components due to the Zeeman effect is difficult, and complete information about the magnetic field direction and magnitude is not obtainable. In this situation, the Stokes V spectrum allows only for the determination of the line-of-sight component of the field strength, $B_{LOS} (= B \cos \theta)$, where θ is the angle between the direction of the magnetic field and the line of sight), and its sign (i.e., toward or away from the observer). It is then reasonable to approximate $RCP - LCP$ by the derivative of I , so that

$$V = \Delta\nu_z \cos \theta \frac{dI}{d\nu} + \beta I \quad (2)$$

$$= \frac{Z}{2} B_{LOS} \frac{dI}{d\nu} + \beta I \quad (3)$$

where βI represents a gain term which introduces a replica of the I spectrum scaled by the factor β into the V spectrum. This gain term is required since in a real experimental setup there will be polarisation leakage due to imperfections within the signal paths and the telescope feeds (linear or circular) (Cotton, 1999; Bhatnagar and Nityananda, 2001; Thompson et al., 2017). Careful calibration of the data following well established polarisation calibration procedures can mitigate this issue so that the scaling factor β is $\ll 1$. The Zeeman effect reveals itself in the V spectrum in the small splitting approximation as a characteristic sideways "S", or "Zeeman pattern" (essentially a derivative of a Gaussian line profile).

An advantage of observing the Zeeman effect at SKA frequencies is that the *frequency offset* due to the Zeeman effect is *independent* of the line frequency, whereas the *Doppler broadened line width* is *proportional* to the line frequency. The ratio of the Zeeman effect to the line width decreases as the frequency of the line increases, and so low frequency lines are preferred.

3 Zeeman Effect Tracers at Frequencies Covered by the SKA Telescopes

As discussed above, the best Zeeman-sensitive thermal-line transitions for tracing magnetic fields typical of those in the ISM and star-forming regions are paramagnetic species with large Landé g -factors that occur at cm wavelengths. Those covered by SKA frequencies and potential upgrades are listed in Table 1. The SKA telescopes will initially cover 50 MHz to 15.4 GHz, while a potential expansion in frequency coverage to ~ 26 GHz or slightly higher is entirely feasible (e.g., see SKAO Memo 20-01 "SKA1 Beyond 15 GHz: The Science case for Band 6"). Strong diamagnetic masers such as CH₃OH and H₂O with small splitting factors are suitable for regions of high magnetic field strength. From Table 1, the Zeeman effect in thermal lines has been definitively detected in the OH lines at 1665 & 1667 MHz, and HI at 1.4 GHz. Claims of detections in the OH 13 GHz (Gusten

Table 1: Zeeman effect tracers at SKA frequencies of relevance to star formation^a

Species	Transition	Frequency (GHz)	Splitting factor (Z^b) (Hz/ μ G)	R.I. ^c
HI	$^2S_{1/2} F = 1 - 0$	1.420406	2.8	1
H/He/C	RRLs	0.05-15.4	2.8	1
CH $^2\Pi_{3/2}$	$J = 3/2, F = 2 - 2$	0.701677	1.81	9
	$J = 3/2, F = 1 - 1$	0.724788 ^d	3.03	5
	$J = 5/2, F = 3 - 3$	4.847768	1.15	10
	$J = 5/2, F = 2 - 2$	4.870059	1.62	7
OH $^2\Pi_{3/2}$	$J = 3/2, F = 1 - 1$	1.665402	3.27	5
	$J = 3/2, F = 2 - 2$	1.667359	1.96	9
	$J = 3/2, F = 2 - 1$	1.720530 ^e	1.31	1
	$J = 5/2, F = 2 - 2$	6.030748 ^e	1.59	7
	$J = 5/2, F = 3 - 3$	6.035093 ^e	1.13	10
	$J = 7/2, F = 3 - 3$	13.434637	1.03	10
C ₄ H	$N = 1 - 0, J = 3/2 - 1/2, F = 1 - 0$	9.49306	2.27	2.5
	$N = 1 - 0, J = 3/2 - 1/2, F = 2 - 1$	9.49762	0.7	7.4
	$N = 1 - 0, J = 3/2 - 1/2, F = 1 - 1$	9.50800	2.53	1.9
	$N = 2 - 1, J = 5/2 - 3/2, F = 2 - 1$	19.01472	0.80	7.8
	$N = 2 - 1, J = 3/2 - 1/2, F = 3 - 2$	19.01514	0.47	12.3
CCS	$J_N = 1_0 - 0_1$	11.119446	0.81	1
	$J_N = 2_1 - 1_2$	22.344033	0.77	1
SO	$J_N = 1_2 - 1_1$	13.04381	1.93	1
OH $^2\Pi_{1/2}$	$J = 1/2, F = 1 - 0$	4.765562 ^e	-0.0033	1
CH ₃ OH	$5_1 - 6_0 A^+$	6.668519 ^e	-0.00114	1
	$2_0 - 3_{-1} E$	12.17859 ^e	-0.001	1
H ₂ O	$6_{16} - 5_{23} F = 7 - 6$	22.235080 ^e	0.0021	1

Table Notes: ^aTable is adapted from Heiles et al. (1993); Robishaw (2008); Crutcher and Kemball (2019) and updated; ^bAll values of Z have been re-calculated, and previously published incorrect values have been updated (e.g., Lankhaar et al. (2018); Lankhaar, in preparation), except H₂O (Fiebig and Guesten, 1989; Nedoluha and Watson, 1992; Sarma et al., 2002); ^cR.I. = Relative Intensity: the relative sensitivity to the Zeeman effect for lines from a single species arising from common levels can be estimated by comparing the product of $Z \times$ R.I.; ^dThe frequency for the CH $J = 3/2, F = 1 - 1$ transition is corrected from that given in Crutcher and Kemball (2019); ^etypically seen as a maser.

et al., 1994) and CCS 22 GHz lines (Koley et al., 2022) exist in the literature but these remain tentative.

3.1 Hydroxyl: OH

The first detection of the Zeeman effect in a thermal molecular transition was with OH at 1665/1667 MHz in absorption against the HII region NGC 2024 (Crutcher and Kazes, 1983). The large Zeeman splitting factors for these transitions, and their ubiquity in absorption and emission at densities typical of molecular clouds ($10^2 - 10^4 \text{ cm}^{-3}$), means they have been the prime tool for surveys of the Zeeman effect in these regions (Crutcher, 1999; Bourke et al., 2001; Thompson et al.,

2019; Troland and Crutcher, 2008; Crutcher et al., 1993), and contribute most of the data shown in Fig 1. Additionally, they constitute all of the secure interferometric molecular Zeeman detections to date (e.g., Roberts et al., 1995; Crutcher et al., 1999a; Sarma et al., 2000; Brogan and Troland, 2001b; Sarma et al., 2013; Koley et al., 2021).

The OH 1665/1667 MHz pair provides two advantages for Zeeman effect measurements. First, they lie close in frequency so they may be observed simultaneously, and second, the ratio of their Zeeman b factors is similar to the inverse of their relative strengths, and so they are approximately equally sensitive to the Zeeman effect. Conversely, it is difficult to separate $N(\text{OH})$ and T_{ex} from observations, unless Local Thermodynamic Equilibrium (LTE) is assumed and the beam filling factor is known. Values of $N(\text{H})$ inferred from $N(\text{OH})$ in Fig 1 are thus uncertain due to the poorly constrained values of T_{ex} (Ebisawa et al., 2019, 2020; Harju et al., 2000).

The excited transitions of OH (4.7 GHz, 6.0 GHz, 13 GHz) listed in Table 1 generally exhibit maser activity (§3.7), whereas thermal absorption is only occasionally weakly seen. The single exception is the absorption toward W3(OH) in the 13.434 GHz line, which shows a clear Zeeman effect detection with an inferred field strength of $+3.1 \pm 0.4$ mG (Guesten et al., 1994). More examples of absorption in this line are needed to trace the field in the high density shocked gas around protostars.

3.2 Methylidene: CH

CH has been a promising candidate for Zeeman observations for many years (Heiles et al., 1993), but this remains unfulfilled due to the lack of detections of the most promising CH line that can showcase Zeeman splitting: the first rotationally excited state ($^2\Pi_{3/2}, N = 1, J = 3/2$) transitions at 701 and 724 MHz (Table 1). To date only weak detections of the CH lines in total intensity using significant observing time have been published. Ziurys and Turner (1985) observed the 700 MHz lines with the Arecibo 305 m telescope toward the HII region W51A with over four days of observations, with follow-up observations using the NRAO 300 ft Green Bank telescope. These observations detected the lines in absorption with intensities < 1 K. One or both of these lines have also been detected toward W51M, W3, W43, and Orion B (Turner, 1988; Ziurys and Turner, 1985), while the W51A detection has been replicated in at 2.5h observations with the GBT (Tremblay et al. in prep.). More recently, Tremblay et al. (2020) used ASKAP to search for the 700 MHz lines toward RCW 38 with negative results, while Jacob et al. (2024) detected them with the uGMRT toward W51, and modelled them alongside the 3.3 GHz ground-state and 560 μm excited state lines using detailed non-LTE radiative transfer calculations. These models indicate that the 700 MHz lines trace relatively high-density gas, around 10^5 cm^{-3} , as predicted (Heiles et al., 1993).

The more commonly detected 3.3 GHz transition is not sensitive to the Zeeman effect for practical purposes, due to small Zeeman splitting factors. While some higher frequency excited state CH transitions do have Zeeman splitting factors of order unity (Lankhaar priv. comm.), they have not yet been detected (e.g., Matthews et al., 1986). Recent detailed modelling suggests they will not be detectable under typical conditions within molecular clouds or the ISM (Jacob et al., 2024).

Although rarely observed, the 700 MHz lines are essential for interpreting the CH pumping cycle, as they directly connect the first excited state to the ground-state levels involved in pumping the 560 μm line (Jacob et al., 2024). Coupled with the well-understood 3.3 GHz maser, they offer a

unique diagnostic of both CH excitation and magnetic fields in regions of high-density molecular gas, a regime currently inaccessible through most other tracers used in the Crutcher relationship (Crutcher, 2012). With the sensitivity offered by future SKA observations, these lines have the potential to provide the first systematic measurements of magnetic fields in envelopes of massive star-forming regions.

3.3 Thioxoethenyldene: CCS

CCS is an early-time chemical tracer, before star formation occurs (e.g., Suzuki et al., 1992; Aikawa et al., 2001; Seo et al., 2019; Chen et al., 2025), tracing densities of a few $\times 10^4$ cm^{-3} in both low- and high-mass star-forming regions. Most observations have been made with its 22 GHz and 45 GHz lines (e.g., Hirota et al., 2009). The CCS lines at 11, 22, 33, and 45 GHz all have Zeeman splitting factors ~ 1 Hz/ μG , and a handful of Zeeman observations have been made, resulting in both tentative and non-detections (Shinnaga et al., 1999; Levin et al., 2001; Nakamura et al., 2019; Koley et al., 2021). A claim of a Zeeman detection in the 11 GHz line toward the prestellar core TMC-1C exists (Guesten and Fiebig, 1990), inferring a field strength of ~ 110 μG with an uncertain g -factor. The line intensity of ~ 2 K measured with the Effelsberg 100-m is encouraging, but almost no other observations of this line have been published (Uchida et al., 2001), and so its utility as a Zeeman tracer remains unclear. The recent GOTHAM survey of the low-mass prestellar core TMC-1 with the GBT shows the strength of the 11 and 22 GHz lines to be similar, at a few K, which is not only encouraging, but surprising, as under LTE conditions the 22 GHz line should be 2–3 times brighter (Xue et al., 2025). In TMC-1 at least the population of CCS transitions deviate significantly from a Boltzmann distribution in a direction that is favourable for the 11 GHz line – there are now many observations of the 22 GHz line as part of large K-band surveys of the ammonia lines (NH_3) using the GBT, and the Nobeyama 45-m, from which the line brightness of the 11 GHz may be inferred (Kaifu et al., 2004; Hirota et al., 2009, 2011; Seo et al., 2019; Pineda et al., 2026). Previous estimates of the utility of the 11 GHz line for SKA-Mid Zeeman observations may be overly pessimistic (see §3.10.2 in SKAO Memo 20-01 "SKA1 Beyond 15 GHz: The Science case for Band 6"), but more observations of the 11 GHz line are needed (section 7.3).

3.4 Other Molecular Zeeman Effect Candidates

Within the frequency range of the SKA telescopes are two other potential Zeeman candidates, the paramagnetic molecules C_4H and SO . There are a number of C_4H transitions around 9.5 and 19 GHz that are sensitive to the Zeeman effect, while SO has a single transition at 13 GHz (Table 1). The 3 hyperfine components of the $N = 1 - 0, J = 3/2 - 1/2$ line of C_4H near 9.5 GHz have an almost equal sensitivity to the Zeeman effect in LTE (the product of their relative intensities and their splitting factors), although the line at 9.497 GHz has a significantly higher intensity. With three lines of almost equal sensitivity to the Zeeman effect, any possible detection of the effect can be confirmed through obtaining the same result in all three components, as shown for the example of the CN 1–0 Zeeman detections at 3-mm (Crutcher et al., 1996b, 1999b), and the OH lines at 1.6 GHz. Further, the three hyperfine components of the $N = 1 - 0, J = 1/2 - 1/2$ line near 9.55 GHz all have Zeeman splitting factors ~ 1 Hz/ μG , and the 9.551 GHz line has a sensitivity to the Zeeman effect that is similar to that of the 9.5 GHz lines, which would provide further support for any Zeeman effect detection in C_4H .

Unfortunately there are very few observations or detections of any of the 9.5 GHz lines (Turner and Heiles, 2006). For example, the GBT spectral line survey of TMC-1 (Xue et al., 2025) detected all six of the 9.5 GHz hyperfine lines in their expected LTE ratios, with a peak of ~ 0.75 K in the 9.497 GHz line. TMC-1 is known to be carbon-rich, so this result may not be typical. A survey of the 9.5 GHz C_4H lines toward molecular cloud cores and protostars, particularly those that are known to be carbon-rich, is needed to assess their practicality as Zeeman effect tracers.

With an extension to the SKA-Mid frequency coverage, the C_4H lines around 19 GHz become interesting as tracers of the Zeeman effect. As for the 9.5 GHz lines, there are very few observations of these lines to determine their practicality as Zeeman effect tracers (Kaifu et al., 2004; Gupta et al., 2009; Xue et al., 2025; Lis et al., 2025), and so surveys are also required at these frequencies. In Table 1 we provided updated values of the Zeeman-splitting factors for the most promising C_4H transitions.

Sulphur monoxide (SO) has been identified as a Zeeman effect candidate for many years (e.g., Clark & Johnson 1974, although their interpretation of the broad SO linewidths in Orion as due to Zeeman broadening was incorrect), and most observations of SO in total intensity have focused on the lines ≥ 30 GHz. Calculations of the SO Zeeman-splitting factors have primarily been for the transitions ≥ 30 GHz (Bel and Leroy, 1989; Shinnaga and Yamamoto, 2000; Chiong, 2003; Cazzoli et al., 2017), while published attempts to observe the Zeeman effect at these frequencies only exist for the 30 GHz line toward DR21(OH) and Orion B (Chiong, 2003), with an unconfirmed detection toward DR21(OH) of -2.1 ± 1.2 mG (i.e., less than a 2σ result).

The SO 13 GHz line has been covered in the deep spectral line surveys of TMC-1 (Kaifu et al., 2004; Xue et al., 2025), but not detected (although the 30 GHz line was detected). As noted above, TMC-1 is carbon-rich, is a starless core, and has a moderate central density. Chemical models predict that SO has a slow chemical evolution and is more likely to be present in evolved sources (protostars) of higher density, a result that seems to be confirmed by observations (Rydbeck et al., 1980; Codella and Muders, 1997; Zinchenko and Henkel, 2018), as well as enhanced in shocks (such as those seen in protostellar outflows, Pineau des Forets et al. 1993), but depleted in HII-only sources (Li et al., 2015b). So TMC-1 may not be a good case study for the presence of SO. Uchida et al. (2001) undertook a survey of the SO 11 GHz line with the Effelsberg 100-m of approximately 50 positions (using short integrations) to find candidates for Zeeman observations, detecting about half of them. Their observations of the Zeeman effect toward 8 sources resulted in no detections. Notably, all their Zeeman effect targets were protostellar sources, supporting the expectation that high-density protostellar regions (including shocks) may be the best for SO detections. Observations of SO at mm/submm wavelengths further support this view (Tang et al., 2024). As is the case for C_4H , larger surveys of the 13 GHz SO line are needed to assess its practicality as a Zeeman tracer.

3.5 HI

The HI 21-cm line was the first spectral line in which the Zeeman effect was detected in the interstellar medium, providing the earliest direct measurements of magnetic fields in the cold neutral medium (CNM) (Verschuur, 1968), from which molecular clouds form. One major advantage of HI Zeeman observations is that the 21-cm line is ubiquitous across the Galaxy, and hence HI

Zeeman observations remain a fundamental tool for tracing magnetic fields in the ISM, particularly the diffuse, atomic phases. In molecular clouds HI Zeeman effect observations are possible in absorption lines seen either against a bright continuum region, such as a HII region, or as self-absorption in cold HI.

In molecular clouds with high-mass star formation, Zeeman effect observations of HI absorption have been made toward photodissociation regions (PDRs) in front of compact HII regions (Roberts et al., 1993; Crutcher et al., 1996a; Brogan et al., 1999; Brogan and Troland, 2001a; Troland et al., 2016), where the bright background continuum emission often results in deep HI absorption lines and enhances the sensitivity of HI to the Zeeman effect. These PDRs are the thin layer between the ionised region around the massive star(s) and the molecular cloud, and thus can trace densities in excess of 10^4 cm^{-3} . These observations typically measure magnetic field strengths of 10s to a few hundred μG .

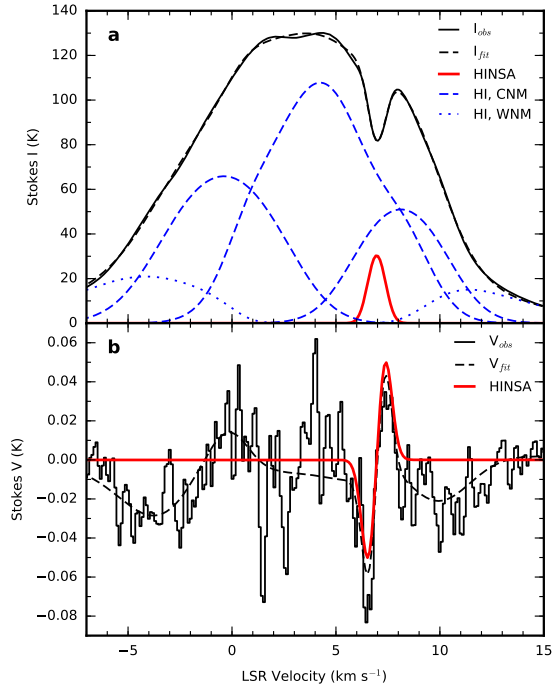
In cold molecular clouds, HI narrow self-absorption (HINSA) has been observed, and the HI and OH survey of dark clouds by Li and Goldsmith (2003) established a correlation between HINSA and the moderate density gas traced by OH ($\sim 10^3 \text{ cm}^{-3}$). Thus HINSA provides another probe of magnetic fields in molecular clouds without high-mass star formation. The advantages of using HINSA as a Zeeman tracer include: (1) the Landé g -factor of HINSA is larger than those of most molecules; (2) the intensity of HINSA is usually stronger than other molecular lines; (3) close to the steady state between H_2 formation and destruction, the number density of HINSA is independent of the gas density, making HINSA a promising probe for tracing magnetic fields inside the dense depletion zone that is inaccessible to other Zeeman tracers. The first HINSA Zeeman effect detection was obtained using the Five-hundred-meter Aperture Spherical radio Telescope (FAST) at $2''.9$ resolution toward the prestellar core L1544 (Ching et al., 2022). The HINSA Zeeman effect gives $B_{\text{LOS}} = +3.8 \pm 0.3 \mu\text{G}$ (Figure 2), comparable to the strengths derived via the Zeeman measurements of HI absorption toward the surrounding CNM gas of the prestellar core L1544, indicating an early transition from a magnetically subcritical CNM to a supercritical core.

For Zeeman observations of HI absorption against compact HII regions and HINSA toward cold dense cores, the high angular resolution of SKA-Mid will allow for precise mapping of magnetic field strengths in these dense regions. These observations may be complementary to those using other tracers, as described in this chapter, or they may be the only probe when the other tracers are not present or too weak.

3.6 Radio Recombination Lines

Radio recombination lines (RRLs) of hydrogen, helium and carbon are potential Zeeman tracers in ionised regions, such as PDRs that trace the interface between HII regions and the surrounding molecular cloud, radio jets ejected by protostars, and the surfaces of proto-planetary disks located near to and being ionised by OB stars (e.g., the Orion proplyds). The magnitude of the Zeeman splitting in RRLs was calculated by Greve and Pauls (1980), who find that for high n lines (> 30) of H, He, and C, the result is the same for $n\alpha$ and $n\beta$ transitions for all species: they all have Landé g -factors = 1 and hence Zeeman-splitting factors of $b = 2.8 \text{ Hz}/\mu\text{G}$, the same as for neutral hydrogen. Many RRLs can be observed simultaneously with SKA-Mid Band 2 (50 lines of $\text{H}\alpha/\text{He}\alpha/\text{C}\alpha$) and

Figure 2: The Stokes I and $V(v)$ spectra of HI 21-cm line toward L1544 (adapted from Ching et al., 2022). (a) The black profile represents the I spectrum. The red profile represents the absorption from the foreground HINSA component. The blue dashed and dotted profiles represent the emission of the CNM and WNM components, respectively. The black dashed profile represents the sum of the absorption and emission profiles. (b) The black profile represents the V spectrum. The black dashed profile represents the sum of the Zeeman splitting profiles of the five components. The red profile represents the Zeeman splitting profile with $B_{\text{LOS}} = +3.8 \mu\text{G}$ of the HINSA component.



Band 5 (25 lines), while SKA-Low covers over 200 transitions, although they may be better suited to lower density media than found in molecular clouds (Thompson et al., 2015; Oonk et al., 2015).

To date there are no published observations of the Zeeman effect in RRLs at cm wavelengths, perhaps due to their general faintness, and observations of many sources of any type will require the sensitivity of the SKA telescopes (Silverglate, 1984; Balser et al., 2016). The detection of the Zeeman effect at mm wavelengths in the H30 α line from the disk of the (presumably) young massive star MWC 349, implying a magnetic field strength of ~ 22 mG (Thum and Morris, 1999), suggests the effect should be observable at radio frequencies in other sources with observations of sufficient sensitivity.

3.7 Masers

Masers, being compact and bright sources, offer the opportunity to measure in situ magnetic fields at high resolution using the Zeeman effect. There is a significant body of literature on magnetic fields in star-forming regions measured via the Zeeman effect in OH, H₂O, and CH₃OH masers. Both H₂O and CH₃OH masers occur in the initial phase of star-forming regions, so they can trace the magnetic field at the very early stages of star formation. It has often been pointed out that masers form in special conditions and therefore the magnetic fields they trace are not representative of the larger environments around them. However, it has been demonstrated that information on the larger-scale magnetic field can be recovered (e.g., Green et al., 2012; Momjian and Sarma, 2012; Goddi et al., 2017; Robishaw et al., 2026)

As a paramagnetic molecule with a large splitting factor, the Zeeman splitting in OH masers can be much greater than the linewidth, such that the OH maser is the only case in which the total field strength can be measured. In all other instances, being maser or thermal lines, only the line-of-sight

component (B_{LOS}) can be measured using the Zeeman effect because the width of the Zeeman splitting is much narrower than the width of the line itself. Observations of the Zeeman effect in OH masers have revealed fields of the order of several mG, e.g., 4 mG in Orion KL at 1612 MHz (Hansen, 1982), 6–10 mG in the compact HII region G49.5–0.4(e2) at 1720 MHz (Benson et al., 1984), 4.7 mG in W3(OH) at 1665 MHz (Harvey et al., 1974) and 0.6–21 mG in 18 Galactic massive star-forming regions at 1665 and 1667 MHz (Fish et al., 2005). In the excited state transitions, Moran et al. (1978) mapped 6.035 GHz maser emission toward W3(OH) at 0'01 resolution and measured magnetic field strengths ranging from 2 to 9 mG, and fields of 0.2–11 mG were found in 30 regions at 6030 and 6035 MHz by Green et al. (2015). Recently, Smits and Fallon (2025) reported a 100 mG field for the 4.7 GHz transition (but their field may be overestimated due to the uncertain value of the Zeeman splitting factor). Another OH transition of interest that will fall within the SKA bands is the 13.4 GHz OH maser, for which Baudry and Diamond (1998) reported a Zeeman detection in W3(OH) (see also §3.1).

The Zeeman effect in the 22 GHz H₂O maser transition was first observed by Fiebig and Guesten (1989) with the 100-m Effelsberg Telescope. Interferometric observations of the Zeeman effect in H₂O masers toward the star-forming region W3 IRS 5 were reported by Sarma et al. (2001) with the VLBA, and were detected for the first time in circumstellar H₂O masers by Vlemmings et al. (2001) with the VLA. Additional observations of 22 GHz H₂O masers carried out over the years (e.g., Sarma et al. 2002; Vlemmings et al. 2005; Alves et al. 2012; Goddi et al. 2017) have revealed magnetic fields in the range of tens to hundreds of mG in a range of star-forming environments.

Class I methanol (CH₃OH) masers are collisionally pumped in outflows in star-forming regions whereas Class II CH₃OH masers are radiatively pumped near the high-mass protostars. Several observations over the years have established that magnetic fields of the order of mG to tens of mG are traced by Class I CH₃OH masers (see, e.g., Sarma and Momjian 2009; Sarma and Momjian 2011; Momjian and Sarma 2017; Momjian and Sarma 2019; Sarma and Momjian 2020) and Class II CH₃OH masers (see, e.g., Vlemmings 2008; Surcis et al. 2009; Vlemmings et al. 2011; Surcis et al. (2015); Surcis et al. 2022).

Several methanol maser transitions (e.g., the bright Class II 6.7 and 12.2 GHz masers) are observable with SKA-Mid, while the sensitivity of SKA-Mid will allow measuring magnetic fields using hitherto unexplored maser lines, such as the Class I methanol maser at 9.9 GHz. Overall, maser Zeeman splitting provides insight to the in situ magnetic fields across a range of evolutionary phases of star formation, and a natural synergy to thermal-line Zeeman measurements (see chapters by Robishaw et al. (2026) and Rygl et al. (2026))

3.8 The Reliability of Zeeman-Splitting Factors

Often a major uncertainty in measuring field strengths via the Zeeman effect is the availability of reliable Landé g -factors, and hence of Zeeman-splitting factors (Table 1). The Zeeman effect is due to the coupling of the molecular/atomic magnetic moment to the magnetic field. The principle magnetic moment that generates the Zeeman effect can either be due to electrons, as in the case of radical species, or nuclei, in other cases. The former are called paramagnetic species, and are associated with Zeeman splittings on the order of a Bohr magneton ($\mu_B/h = 1.4 \text{ Hz}/\mu\text{G}$), while

the latter are called diamagnetic species, and have Zeeman splittings on the order of the nuclear magneton ($\mu_N/h = 0.76$ Hz/mG, i.e., ~ 1500 smaller). The exact scaling of the Zeeman effect with the respective magneton is particular to the transition and is captured in the Landé g -factor.

Determining the Landé g -factor for a transition can be trivial for some species, but difficult for others. Paramagnetic species have magnetic moments due to (an) unpaired electron(s). In atomic species, the electrons are endowed with magnetic moments due to both the orbital angular momentum and the internal spin angular momentum. For light nuclei, and singly unpaired electrons, quantum numbers of the orbital and spin angular momenta are well-defined, leading to the relatively easy evaluation of the total magnetic moment due to the electron. For molecular radicals, things start to get more complicated. Electron angular momenta couple with the molecular rotation (and perhaps any nuclear magnetic momenta), resulting in so-called fine structure. For such species, electronic quantum numbers are not well-defined but approximate. In order to compute the g -factor for a certain transition, the exact mixing of the electron angular momentum states has to be derived, which usually is possible in the case that the fine-structure spectrum is experimentally known (Larsson et al., 2019; Larsson and Lankhaar, 2020). Transition-specific g -factors derived in this way are highly reliable. Finally, there are some molecules, such as C_4H , that have electronic configuration-states that lie close in energy (Oyama et al., 2020). For these molecules, fine structure is determined by a mix of the electronic states, coupling to the rotation, and computing magnetic moments due to unpaired electrons becomes highly non-trivial.

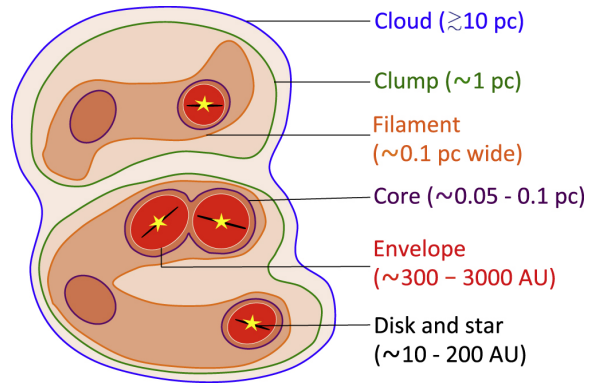
For diamagnetic molecules, the Zeeman effect is due to the magnetic moments of the nuclei. Their sensitivity to the Zeeman effect is significantly less than for paramagnetic species, so that the splitting is only observable in bright maser lines like those of CH_3OH and H_2O (§3.7 & Table 1), with accurate Landé g -factors (e.g., Lankhaar et al., 2018). The values of the Zeeman-splitting factors listed in Table 1 are at present the most accurate available. In cases where only an estimate is given, the derivation of an accurate value is a work in progress (Lankhaar, in prep.).

4 Regions for Study (and their Zeeman Effect Tracers)

4.1 Molecular Clouds

Stars form in dense, compact regions within large molecular clouds (≥ 10 pc). Molecular clouds are hierarchical, likely due to fragmentation (Dobbs et al., 2014). Within molecular clouds are "clumps" (~ 1 pc) which contain elongated "filaments" of width ~ 0.1 pc, to within a factor of 2 (Arzoumanian et al., 2011). Some filaments converge into "hubs" of size a few $\times 0.1$ pc, in which clusters of stars may form. Along the filaments are found "dense cores" of size ~ 0.05 - 0.1 pc (di Francesco et al., 2007) in which individual protostellar systems (hereafter, protostars) form. Cores without stars are starless but those that are gravitationally bound are called prestellar cores, although observationally this is difficult to determine. Starless cores with central densities $> 10^4$ cm^{-3} are likely to be prestellar. Surveys, primarily with Herschel, have revealed that more than 70% of protostars and prestellar cores are found within filaments (André et al., 2014). Protostars are surrounded by "envelopes" of size a few thousand au, from which they directly accrete. Figure 3 presents a not-to-scale cartoon of the hierarchical structure of a molecular cloud as described here.

Figure 3: A cartoon display of a molecular cloud showing hierarchical structures inside the cloud. The figure shows the cloud, clumps, filaments, cores, envelopes, and protostellar systems that we consider in this study. The image is not drawn to scale (from Pokhrel et al., 2018).



Dust polarisation maps show that magnetic fields in the gas surrounding dense filaments (sheaths) are typically aligned perpendicular to the main axis of the filament at column densities $N_{\text{H}} < 5 \times 10^{21} \text{ cm}^{-2}$, becoming more aligned at the edges of the filaments as column densities increase above this number (Planck Collaboration et al., 2016; Pattle et al., 2023). This result leads to the question of whether the fields are shaped by the flow of gas, or whether the fields control the flow of gas, both outside and inside the filaments. Simulations suggest these alignments primarily occur when the magnetic field is dynamically important, so that the fields control the flow of gas (Soler et al., 2013). Measurements of magnetic field strength would greatly assist in answering this question. With SKA-Mid, the gas at moderate column density around the dense filaments can be observed in OH emission or absorption depending on the gas temperature (Ebisawa et al., 2020). Depending on the exact structure (its smoothness) and temperature of the gas, it may also be observed in HI, if it is not strongly spatially filtered.

4.2 Low-mass Star-forming regions

Low-mass star formation occurs within cores of size $< 10 M_{\odot}$, both in isolation ($\sim 1-2$ cores per clump) and in clustered environments. While low-mass stars also form in regions of high-mass star formation, here we are focussed on regions without high-mass stars, such as the nearby molecular clouds of the Gould Belt with distances typically < 300 pc (southern sky examples accessible to the SKA include Lupus, Corona Australis, Ophiuchus, & Chamaeleon).

The classical picture of relatively isolated star formation starts with a dense starless core threaded by a magnetic field that increases in central density until gravity becomes dominant and the core collapses. In this simple picture, the evolution of the core can be slow or fast depending on the strength of the magnetic field, but in either scenario the magnetic field evolves into an hour-glass shaped field with the pinch at the location of the protostar (or in the case of a prestellar core, where the protostar is forming, i.e., the density peak). This field structure has been observed in polarised dust emission in some protostellar cores (Girart 2006) and perhaps in a prestellar core (Kim et al., submitted), but most cores show more complex structures (protostars) or almost parallel fields (prestellar/starless cores). Dense cores are dominated by thermal motions, showing molecular line widths that are usually sub-sonic (and sub-Alfvénic) but can be trans-sonic in the presence of a protostar. The line widths are thus narrow and favourable for Zeeman effect observations.

In low-mass starless/prestellar cores the best tracer of the Zeeman effect is likely to be CCS, as

it traces the right densities and is abundant in chemically unevolved regions (Suzuki et al., 1992). Attempts to observe the Zeeman effect using CCS have been made toward TMC-1 and L1498 (Guesten and Fiebig, 1990; Koley et al., 2022; Shinnaga et al., 1999), while surveys find bright CCS toward some cores, with CCS/NH₃ ratios suggesting they are chemically young (Suzuki et al., 1992; Foster et al., 2009; Marka et al., 2012; Seo et al., 2019). CH and C₄H are promising candidates for Zeeman effect observations toward starless cores, but as indicated earlier, insufficient total power observations of Zeeman sensitive transitions of these molecules exist to know for sure.

In the envelopes (clumps) around dense cores, OH emission has been used to observe the Zeeman effect, in both starless and protostellar cores (Crutcher and Troland, 2000; Bourke et al., 2001), but this emission may be resolved out by SKA-Mid, and simulations are required to examine this. HINSA is a promising probe of magnetic fields in low-mass star-forming regions, as already demonstrated by the FAST results (Ching et al., 2022) toward the prestellar core L1544. HINSA has been shown to originate in the cold, well-shielded interiors of dark clouds, and toward low-mass cores, HINSA is often found to have the same non-thermal line width and the same line centroid velocity as the OH emission (Li and Goldsmith, 2003) and generally follows the distribution of the ¹³CO and C¹⁸O emission (Goldsmith and Li, 2005), all of which trace densities $\sim 10^{3-4} \text{ cm}^{-3}$.

4.3 High-mass Star-forming Regions

High-mass stars (i.e., ionising, with $M > 8 M_{\odot}$ and $L \geq 10^3 L_{\odot}$) form in massive regions of high column density (Beuther et al., 2007; Motte et al., 2018; Urquhart, 2024), the "hubs" discussed earlier where filaments are observed to converge ($\sim 1000 M_{\odot}$). These hubs contain one to a few massive dense cores (MDC) with sizes 0.1-1 pc, from which high-mass protostars form. High-mass stars always form in a clustered environment with lower mass stars, with a distribution generally following the IMF in slope - but clusters don't always form high-mass stars. Whether high-mass star formation (HMSF) is analogous to low-mass star formation is an open question (Beuther et al., 2025), but there is at least one key difference. High-mass stars reach the main sequence while still embedded in and accreting from their natal MDC. Therefore the picture of HMSF is complicated by the competing forces of radiation pressure and accretion. Observationally it can be difficult to study HMSF as most of these regions lie at larger distances than low-mass regions, they contain protostellar clusters of a few hundred to over 1000 members, making it difficult to disentangle cluster and protostar properties, and for the more evolved regions they contain some form of HII region. Hubs containing MDCs, before a high-mass protostar forms, have been identified in both cold dust emission at submm/mm wavelengths and as FIR/MIR dark clouds against the Galactic infrared emission (IRDC - Infrared Dark Clouds), with a very strong correlation between the dust emission and absorption, and with column densities (and hence masses) significantly higher than measured in low-mass clumps & cores. These regions are usually termed "infrared-dark" or IR-dark MDCs, to distinguish them from the larger IRDC in which they reside. High-mass protostars that form in MDCs, before they reach the main sequence and produce strong radio continuum emission, are identified via their bright FIR/MIR infrared emission, and so in this evolutionary phase they are called "infrared-bright" (an IR-bright MDC may and usually does reside in an IRDC). This IR-bright MDC might contain a compact hot molecular core ($> 100 \text{ K}$) surrounding the protostar, rich in spectral lines of complex molecules. As the high-mass protostar grows (accretes) it eventually

becomes massive enough to ionise its surroundings, and is now both infrared-bright and detectable in the radio. It will then evolve and expand from a hyper-compact HII region to an ultra-compact HII region to a compact HII region to the classical HII region which may contain multiple sites of high-mass star formation (Churchwell, 2002; Urquhart, 2024).

Masers are important tools in the study of high-mass regions, and the presence or absence of certain masers is used as a proxy for their evolutionary status (Breen et al., 2010; Urquhart, 2024). As the high-mass star evolves through the hot molecular core phase into the HII region phases, the maser lines of CH₃OH and OH (and H₂O) appear under certain physical conditions and as discussed in §3.7 can provide important information on magnetic field strengths that are complementary to Zeeman effect measurements in non-maser lines.

All of the tools discussed earlier to observe the Zeeman effect and hence measure magnetic field strengths are applicable to HMSF regions. In the earliest phase before the onset of ionising radiation, CCS is a promising candidate for Zeeman observations, showing moderate total intensity emission in regions of high-density cold gas (Sakai et al., 2008; Worthen et al., 2025). Both CH and C₄H are promising candidates in this regard, but as with low-mass regions, surveys of total intensity are required before dedicated Zeeman observations are attempted. SO as both a high density and shock tracer is also promising for HMSF regions, in particular the early cold phase and the hot molecular core phase, and surveys in this line should be undertaken (Fontani et al., 2025). Throughout the HII region phases, absorption line observations of HI and OH are important, as they have already produced many of the Zeeman effect detections to date (Fig 1). These absorption studies are sensitive to the thin PDR layer between the HII region (densities $\sim 10^4 \text{ cm}^{-3}$) and the surrounding molecular cloud and thus provide information on the field at the edge of the HII region. Within the HII region itself Zeeman effect observations of RRLs may be a tool for SKA (Low and Mid) studies of the ionised gas.

4.4 Protoplanetary Disks

Understanding the structure and strength of magnetic fields in protoplanetary disks (PPDs) is important for constraining theories of disk evolution that are strongly based on the favoured mechanism of magnetohydrodynamic (MHD) instabilities (Teague et al., 2025). While dust polarimetry is now routinely used to trace field structure on different size scales in molecular clouds (§5.1), in PPDs the continuum polarisation is often due to other physical effects such as self-scattering. While line-broadening due to the Zeeman effect holds promise for inferring field strengths in some disks (§5.4), it would be preferable to measure field strengths more directly via the Zeeman effect. In non-maser lines, this will be (and has been) challenging for two main reasons.

First, the unpolarised total intensity of SKA Zeeman sensitive tracers is typically not large in PPDs, for transitions observed at higher frequencies (SO, CCS), and so their sensitivity to the Zeeman effect is low, although many transitions of Zeeman sensitive species have not yet been observed toward PPDs at SKA frequencies to know if that holds true at lower-frequencies. While RRLs may be important for studies of disks that are externally radiated e.g., near to OB stars such as the Orion proplyds, as with RRLs in other regions their total intensity may be too low to be useful for Zeeman observations of PPDs (Garufi et al. 2026). HI at 21-cm has not yet been detected in a PPD, and so

is unlikely to be a useful Zeeman tool.

Second, the field geometry in PPDs is complex, with both poloidal and toroidal components, and field reversals, present in even a synthesised beam from an interferometer (Mazzei et al., 2020). Thus it may be that the Zeeman effect is only detectable in PPDs with a particular geometry, such as face on, where the field is aligned with the observer, although initial observations at ALMA frequencies of the face-on disk of TW Hya have proved unsuccessful (e.g., Vlemmings et al., 2019).

5 Synergies with Other B -field Tracers and Other Facilities

5.1 Dust Polarimetry

Dust polarimetry is a widely-used technique for mapping plane-of-sky magnetic field direction (\hat{B}_{POS}), using the preferential alignment of interstellar dust grains with respect to the local magnetic field direction (Davis and Greenstein, 1951; Andersson et al., 2015). This method can be used both in the optical/near-IR by measuring the polarization of background starlight caused by selective dust extinction, or in the far-IR to mm by observing linearly polarized thermal dust emission. Current- and recent-generation (sub)mm and far-IR facilities with polarimetric capabilities have over the last decade significantly enhanced our understanding of the morphology and dynamic importance of magnetic fields in star-forming regions (Pattle et al., 2023). Starlight polarization measurements combined with dust reddening measurements and GAIA-measured parallax distances, have been used to perform polarization tomography, decomposing the observed polarization into multiple “screens” of polarized dust, each with a different distance along the line of sight and magnetic field orientation (e.g. Panopoulou et al., 2019; Angarita et al., 2025; Panopoulou et al., 2025). In the SKA era new polarized emission surveys from CCAT/PrimeCam (CCAT-Prime Collaboration et al., 2023) and Simons Observatory (Ade et al., 2019; Clancy et al., 2023) will map most of the Southern Sky providing arcminute or better resolution \hat{B}_{POS} maps of tens of thousands of dense cold clumps and filaments. Proposed (sub)mm/far-IR polarization-sensitive cameras may provide significant improvements in both angular resolution and sensitivity over current-generation instrumentation, such as those proposed for the Probe far-Infrared Mission for Astrophysics (PRIMA) (Burgarella et al., 2024), for the Atacama Large-Aperture Submillimeter Telescope (AtLAST; Mroczkowski et al. 2025), and future ALMA wideband upgrades (Carpenter et al., 2023). Therefore, SKA Zeeman observations will arrive in a context where plane-of-sky magnetic field direction will have been mapped with high sensitivity and angular resolution over a large fraction of the sky (e.g., Klaassen et al., 2024; Pattle et al., 2025).

While dust polarimetry can provide rapid mapping of plane-of-sky magnetic field morphology, it can only indirectly measure magnetic field strengths using the DCF method (Davis, 1951; Chandrasekhar and Fermi, 1953). This method, while widely used, is subject to many known observational biases, and despite significant recent improvement efforts is likely to be accurate only to within a factor of a few (e.g., Liu et al., 2022; Pattle et al., 2023). Calibration of the DCF method could be significantly improved through benchmarking against Zeeman measurements in as wide a range of astrophysical environments as possible. However, previous attempts to do so have been limited by the prohibitively small number of Zeeman measurements presently available, and the need to ensure that the Zeeman and DCF measurements trace the same material (Poidevin et al., 2013). Moreover,

this benchmarking must be performed statistically since the Zeeman effect and dust polarimetry trace orthogonal magnetic field components (Crutcher et al., 2004). The SKA will provide an unprecedentedly large sample of Zeeman-measured magnetic field strengths across a wide range of gas densities, offering the possibility of accurately calibrating this widely used technique.

Dust polarization also encodes information on the inclination angle of the magnetic field with respect to the plane of the sky, γ , through the polarization fraction, which is proportional to $\cos^2 \gamma$ (Lee and Draine, 1985; Fiege and Pudritz, 2000). If the dust properties can be assumed to be uniform across the cloud then measurements of the polarization fraction can be used to estimate the average inclination angle of a cloud (Chen et al., 2019; Sullivan et al., 2021). More recently Hoang and Truong (2024) have developed a modification of the Chen et al. (2019) method that also includes variations due to grain shape and alignment efficiency. Combining Zeeman measurements of B_{LOS} and constraints on the inclination angle due to dust polarization can be used to estimate the 3D magnetic field strength.

5.2 Faraday Rotation

A complementary technique for studying the line-of-sight magnetic field is the Faraday rotation of linearly polarized radiation in a magnetized plasma. In a simple scenario, when linearly polarized light from a background source passes through a Faraday-rotating medium, the amount of rotation ($\Delta\theta$) has a linear relationship with wavelength squared (λ^2), and the slope is referred to as rotation measure ($\text{RM} = \Delta\theta/\Delta\lambda^2$). Van Eck et al. (2023) provide a consolidated catalog of RMs to-date with more than 55,000 observations. This number is already being significantly increased with the upcoming rotation measure maps from the Polarisation Sky Survey of the Universe's Magnetism (POSSUM; Jung et al., 2024; Vanderwoude et al., 2024; Gaensler et al., 2025) and SPICE-RACS (with over 250,000 RMs; Thomson et al., 2023) with the SKA precursor ASKAP.

Faraday rotation of these background sources can measure the line-of-sight magnetic fields through molecular clouds using the MC-BLOS technique (Tahani et al., 2018, 2025). The technique has two components for determining line-of-sight magnetic fields: 1) direction determination, and 2) strength determination. The direction determination incorporates an on-off approach for determining the RM induced by a cloud's magnetic field at each RM point. The strength determination utilizes column density (extinction) maps and a chemical evolution code. The application of the MC-BLOS technique to some nearby molecular clouds yielded results consistent with Zeeman observations and found a B_{LOS} reversal across the Orion A, California, and Perseus molecular clouds (Tahani et al., 2018). This reversal was previously detected around the Orion A cloud using HI Zeeman observations. The follow-up 3D field reconstruction studies found that an arc-shaped field morphology around the cloud is causing this observed reversal (Tahani, 2022; Tahani et al., 2022b,a). Future RM studies, made with the SKA telescopes, can be strongly complemented by atomic and molecular Zeeman observations (see chapter by Tahani et al. (2026)).

5.3 The Goldreich-Kylafis Effect

In the presence of a magnetic field, molecular rotational levels may split into magnetic sub-levels. Radiation emitted by transitions between these sub-levels may be polarized either parallel or perpendicular to the plane-of-sky magnetic field direction in the presence of an anisotropic velocity

gradient and/or radiation field. This spectral line linear polarisation is known as the Goldreich-Kylafis (GK) effect (Goldreich and Kylafis, 1981; Heiles et al., 1991), and should be observable in many spectral lines with optical depth close to unity. The GK effect offers the possibility of a velocity-resolved tracer of plane-of-sky magnetic field morphology, but interpretation is complicated by the uncertainty on polarization direction, and due to the weakness of the effect, it has thus far been observed only in (sub)mm lines (Girart et al., 1999; Ching et al., 2016), and not at all at cm wavelengths accessible to the SKA. In regions where both the GK and Zeeman effect are detected they offer the promise of complementary (plane-of-sky and line-of-sight) velocity-resolved information on the magnetic field, but this promise awaits realisation.

5.4 Line Broadening due to the Zeeman Effect

Although the main signature of the Zeeman effect on spectral lines is a frequency offset of the RCP and LCP components in proportion to the LOS field strengths and Landé g -factor, the Zeeman effect leaves additional signatures in spectral lines (Lankhaar and Teague, 2023). First, the shifting of polarization modes also produces linear polarization, which scales with the square of the plane-of-sky field component. The expected linear polarization fraction is of order $\sim \Delta Q [V/I]^2 [B_{\text{POS}}^2/B_{\text{LOS}}^2]$, where ΔQ is a proportionality factor, that can become very large for lines with transitions that are associated with large angular momenta (Lankhaar and Teague, 2023). Usually, linear polarization fractions are low, but they can become high for sources with a favorable geometry and for transitions that are sensitive to linear polarization. Second, Zeeman splitting broadens the spectral line in proportion to the square of the total field strength: that is of order $\Delta v_Z/\text{FWHM} \sim \bar{Q} [V/I]^2 [B_{\text{TOT}}^2/B_{\text{LOS}}^2]$, where \bar{Q} is the broadening factor, which can become very large for lines with transitions that are associated with large angular momenta. Measuring the Zeeman broadening across a manifold of CN $N = 1 - 0$ transitions with varying Zeeman sensitivities has successfully constrained the magnetic field strength of the protoplanetary disk TW Hya (Teague et al., 2025). If multiple Zeeman signatures (circular polarization, linear polarization, and line broadening) can be measured simultaneously, they together enable a full 3D characterization of the magnetic field from a single tracer (Lankhaar and Teague, 2023).

5.5 Zeeman Tracers at non-SKA Frequencies

Zeeman effect observations at frequencies higher than those covered by the SKA have been successfully performed using the septet of CN lines at 113 GHz with the IRAM 30-m telescope (Crutcher et al., 1996b, 1999b), and with H₂O masers (§3.7). There are a number of transitions in the 13, 7 and 3 mm bands that are potential Zeeman tracers of high-density and shocked gas, notably CCS at 22, 33, and 45 GHz (including Zeeman observations in the 22 GHz and 45 GHz lines; Shinnaga et al. (1999); Levin et al. (2001); Nakamura et al. (2019); Koley et al. (2022)), SO at 30, 86, and 99 GHz, and the C₂H triplet at 87 GHz (Robishaw, 2008; Crutcher and Kemball, 2019). Attempts have been made to detect the Zeeman effect in the CN lines with ALMA, without success. The CCS and SO lines, having Zeeman sensitivity transitions at SKA frequencies, offer the potential of measuring the field strength in multiple transitions of the same molecule. There now exists a number of ALMA surveys in the 3-mm band covering some of these lines, such as the ALMA-ATOMS survey of high-mass star forming clumps (Liu et al., 2020) which provide catalogs for identifying Zeeman candidates. Future surveys with ALMA and eventually AtLAST will identify new candidates, and

deep Zeeman observations should be undertaken with both facilities, while keeping in mind the polarisation sensitivity limits of ALMA (see the ALMA Technical Handbook).

6 Metrics

The review by [Pattle et al. \(2023\)](#) discusses in detail how observations of magnetic fields are used to understand their importance in molecular cloud formation and evolution, and in star formation. Here we focus on a few key areas where magnetic field strength measurements via the Zeeman effect with the SKA will provide crucial information for advancing our understanding of the role of magnetic fields in star formation.

As noted earlier, the number of *detections* of the Zeeman effect in [Fig. 1](#) is small, and the main goal is to increase the number of measurements on multiple size-scales and densities within molecular clouds. With the SKA this means undertaking Zeeman effect observations on scales of clumps (1 pc and 10^3 cm^{-3}) to the scales and densities of envelopes around protostellar systems, and perhaps the disks around protostars ([Fig. 3](#)). While the $B - n$ and $B - N$ data in [Fig. 1](#) suggests that molecular clouds on most size scales are magnetically supercritical and undergoing self-similar collapse ($\kappa \sim 0.65$), the small number of data points, and arguments suggesting issues with both the data (density estimates) and analysis, means these results are not conclusive, and could even be consistent with a $B - n$ index of $\kappa \sim 0.5$ ([Tritsis et al., 2015](#)). The relationships may even suggest fields are about critical for more realistic geometries such as non-uniform densities ([Myers and Basu, 2021](#)). It is not clear if these relationships hold within individual regions, as maps and measurements at different densities are mostly lacking. Attempts to infer the $B - n$ relationship within individual clouds using the DCF method suggests the relationship could exhibit a shallower index of 0.5 (e.g., [Li et al., 2015a](#)), while global DCF results are broadly consistent with $\kappa \sim 0.6$, with significant scatter ([Pattle et al., 2023](#)).

Another measure of the importance of magnetic fields is the mass-to-magnetic flux ratio ($M/\Phi \propto N_{\text{H}}/B$), which is a measure of the ratio of gravitational to magnetic pressure ([McKee et al., 1993](#)), and provides a straightforward way to determine whether magnetic fields are strong enough to support clouds against gravity. The critical mass-to-flux ratio is the ratio for which the gravitational and magnetic energies are in equilibrium, $(M/\Phi)_{\text{crit}} = c_{\Phi}/\sqrt{G}$, where the numerical value c_{Φ} depends on the cloud geometry, being ≈ 0.12 for a uniform spherical cloud with flux-freezing, and ≈ 0.16 for an isothermal sheet with a constant mass-to-flux ratio ([Bourke et al., 2001](#)). The mass-to-flux ratio is usually expressed in terms of the critical value,

$$\mu_{\Phi} = \frac{(M/\Phi)}{(M/\Phi)_{\text{crit}}} = \frac{\sqrt{G} N_{\text{H}}}{c_{\Phi} B} \quad (4)$$

with correction factors of a few for geometry ([Bourke et al., 2001](#)). Values of $\mu_{\Phi} > 1$ indicate the field cannot prevent gravitational collapse, and the region is called magnetically supercritical, while values < 1 indicate a magnetically subcritical region ([Fig 1\(b\)](#)). Experimentally values of $\mu_{\Phi} \lesssim 2$ are generally considered to be consistent with being approximately critical, and thus magnetic fields play a role in regulating cloud collapse. While many regions observed to date are formally supercritical by a factor of 2-3, they may still slow collapse without preventing it ([Myers and Basu, 2021](#)).

Because Zeeman observations use spectral lines, information on line width and hence velocity dispersion is obtained, while the field strength measurements allow for the determination of the Alfvén velocity. This information enables the determination of the Alfvén Mach number M_A , the ratio of non-thermal velocity dispersion and Alfvén velocity, which is a measure of the relative importance of kinetic and magnetic energies. In general, values of $M_A < 1$ (sub-Alfvénic) implies that magnetic fields direct gas motions, while $M_A > 1$ indicates the gas guides the fields (super-Alfvénic). The relative importance of magnetic fields in the support and evolution of molecular clouds on different scales can be judged by determining how close the different energy densities (magnetic \mathcal{M} , gravitational \mathcal{G} , and kinetic \mathcal{K}) are to equipartition (Myers and Goodman, 1988; McKee et al., 1993). By comparing maps of magnetic field strength distribution with velocity structure maps and density distribution maps (column and number densities), one can examine the relative contributions of \mathcal{M} , \mathcal{G} , and \mathcal{K} from diffuse envelopes to dense cores. Such comparisons will help quantify how energy is transferred and dissipated during star formation.

7 Predictions for measuring magnetic field strengths with the SKA

The $3\text{-}\sigma$ sensitivity of Zeeman effect observations to a particular value of the magnetic field strength can be estimated using the following equation (Troland and Heiles, 1982):

$$B_{min} [\mu\text{G}] = 2 \left[\frac{1}{Z} \right] \left[\frac{FWHM}{1 \text{ Hz}} \right] \left[\frac{\Delta I}{I} \right] \quad (5)$$

where I is the line intensity, ΔI is the rms (or equivalently, $\Delta I/I$ is the inverse of the S/N ratio), the line width is in Hz, and the spectral resolution allows for 6 channels across the line FWHM.

The combination of sensitivity and resolution offered by the SKA covering a number of Zeeman-sensitive transitions (Table 1) promises to significantly increase in the number of Zeeman effect detections in the different types of star-forming environments discussed in §4 over a range of densities and size scales. Below we present some case studies using the SKA-Mid AA4 to illustrate this.

7.1 Case study 1: OH Zeeman effect in Orion B - the Gold standard

The Zeeman effect has been well-detected in OH absorption toward the HII region Orion B (NGC 2024; 380 pc) with a number of facilities (Nançay, Parkes, Green Bank 140-ft, VLA; Crutcher and Kazes, 1983; Bourke et al., 2001; Crutcher et al., 1999a). Using the VLA, Crutcher et al. (1999a) were able to map the Zeeman effect in Orion B down to $\sim 10 \mu\text{G}$, with a peak value of around $90 \mu\text{G}$, with $\sim 60''$ resolution (Fig. 4). Their observations, combining the VLA C+D configurations, had an on-source integration time of ~ 21 hrs, resulting in a per-channel rms noise of ~ 6 mJy/beam (0.15 km/s channels). With MeerKAT this noise can be achieved in ~ 0.5 hr with the same beam size (but with 0.29 km/s channels), and because of its array layout, that same sensitivity is still achieved with only a $10''$ beam. Ultimately, with the SKA-Mid a similar sensitivity can be obtained in a $\sim 6''$ beam (0.012 pc) in only 5 minutes (a factor ~ 10 improvement in resolution). With SKA-Mid, consideration may need to be given as to whether such a short integration provides suitable (u,v) coverage for an extended source, and the time needed for polarisation calibrations. This analysis

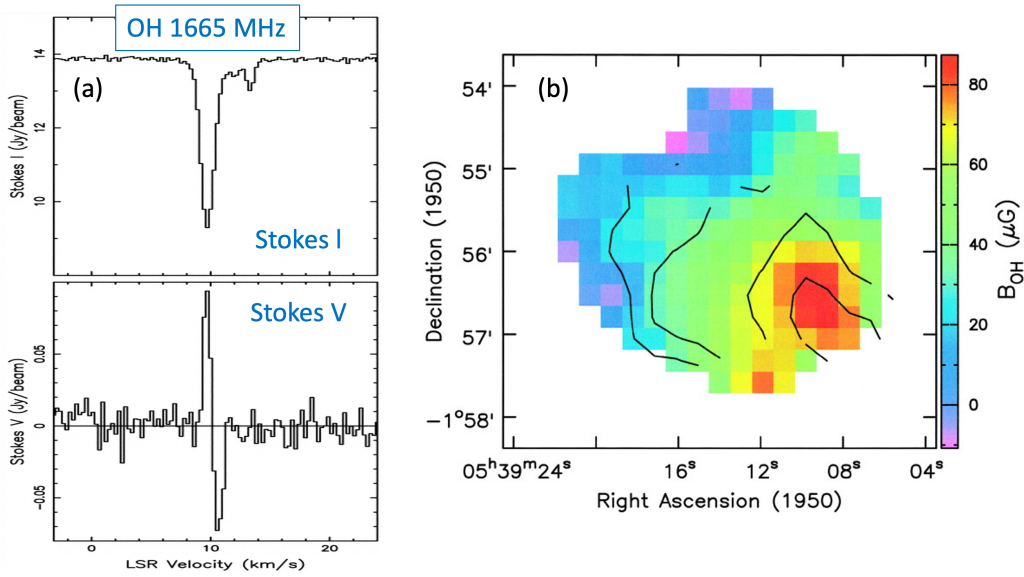


Figure 4: OH Zeeman measurements toward NGC 2024 using the VLA with a beam size of $\sim 60''$. Figure adapted from Crutcher et al. (1999a). Panel (a) shows the OH 1665 Stokes I and V spectra at the position of the peak field, while (b) shows the map of derived field strength. SKA-Mid will obtain similar results in a fraction of the time with a $\sim 6''$ beam.

is the subject of a separate effort beyond this paper. Deeper SKA-Mid observations will allow for mapping of the field down to μG levels on these scales.

7.2 Case study 2: OH Zeeman effect in DR21

Most Zeeman detections in thermal (i.e., non-maser) lines are not as clear as the Orion B case. An excellent example is the recent detection of the OH Zeeman effect toward DR21 (Koley et al., 2021), one of the few new detections since the Crutcher review (Crutcher, 2012). Koley et al. (2021) used the VLA with spectral resolution of 0.175 km s^{-1} in the D-configuration (beam $\sim 30''$) with an on-source integration time of ~ 8 hr, resulting in an rms noise of ~ 10 mJy. As they observed both OH 18 cm mainlines, they were able to confirm their detection of a field strength of $\sim 130 \mu\text{G}$. The line profile is complex, requiring at least 5 Gaussian components to fit the main absorption line (negative velocities), with the deepest fitted absorption line giving rise to the Zeeman effect. The Zeeman signal and fit might not look convincing (Fig. 5) but the formal results are secure, as confirmed by our simulation with similar parameters. A similar result could be achieved with the SKA-Mid with only a 6 minute integration (with an rms noise < 5 mJy in a smaller beam $< 20''$.) With significantly more integration time SKA-Mid will be sensitive to much lower field strengths (e.g., $20 \mu\text{G}$ in 24 hrs for spectra $10 \times$ fainter), allowing for mapping of the field toward nearby (≤ 2 kpc) high-mass star-forming regions similar to DR21.

7.3 Case study 3: CCS Zeeman effect at 11 GHz in star-forming cores with SKA-Mid

Surveys of the higher-frequency CCS lines (> 11 GHz) suggest that CCS traces mean densities of $3 \times 10^4 \text{ cm}^{-3}$, and shows typical linewidths of $\sim 0.7 \text{ km s}^{-1}$ and $\sim 0.2 \text{ km s}^{-1}$ for low-mass protostellar and prestellar cores, respectively (and $\sim 1.5 \text{ km s}^{-1}$ in infrared dark clouds). Using this

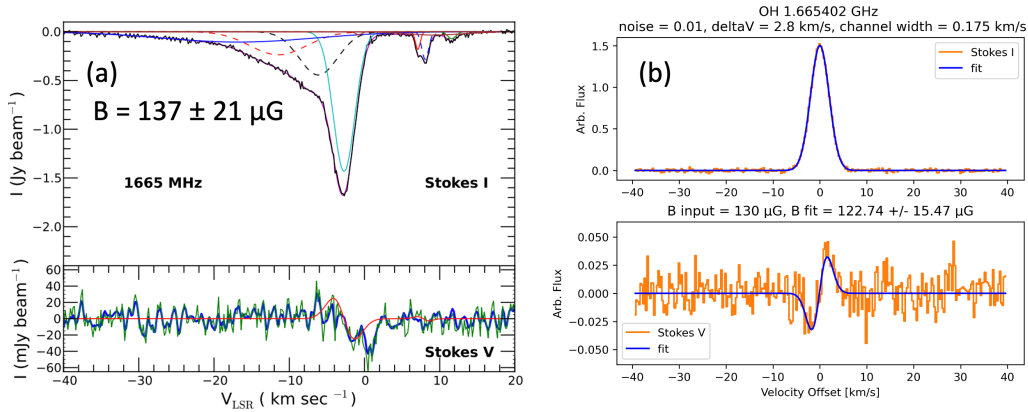


Figure 5: (a) OH Zeeman measurements toward DR21 using the VLA (adapted from Koley et al., 2021). (b) Simulated spectra of the DR21 result, confirming the robustness of the VLA result (the simulation is agnostic to whether the input profile is "emission" or "absorption" as the ultimate result is the same).

mean density, assuming the source completely fills the beam (reasonable for the relatively shallow inner density profiles of low-mass cores, at least) and shifting the Crutcher relationship ($B \propto n^{0.65}$) down by 0.5 dex (to ensure we are sensitive to a field strength well below the 0.65 line – see Fig 1), we simulate the S/N and hence time required with SKA-Mid to detect a field of 300 μG and 100 μG (3σ) for protostellar and prestellar low-mass cores, respectively, with a peak line flux of 0.5 Jy in a 30'' beam (equivalent to a ~ 1 K line observed with the GBT). In the protostellar case an integration time of ~ 3 hrs is needed, and ~ 8 hrs for the prestellar case. If the line is only 0.2 Jy then the times increase to ~ 20 hrs and ~ 65 hrs respectively. The limited observations of the 22 GHz line using both the GBT with $\sim 30''$ beam and the VLA with $\sim 4''$ beam suggest that the VLA filters out most of the single-dish emission, supporting the assumption that the density distribution is relatively flat. The dense inner core of SKA-Mid will alleviate some of the interferometric filtering issues, but quantifying this will require simulated observations with the SKA-Mid layout of star-forming cores whose density profiles are well modelled, which is beyond the scope of this chapter but is a work in progress.

7.4 Zeeman Effect Observations with the SKA – Plans and Preparations

It is difficult to make clear predictions on the number of new Zeeman detections that will be made with the SKA (AA4) before the surveys below are undertaken. The expectation is that several hundred new detections will be made, with maps in the different density tracers in individual regions. Observations of the Zeeman effect with the SKA will primarily be undertaken with SKA-Mid (Table 1). SKA-Mid's frequency coverage and instantaneous bandwidth will allow for multiple species to be observed in a single observation, e.g. the 13 GHz lines of OH and SO, the 9 GHz lines of C₄H and methanol, and the 11 GHz line of CCS in Band 5b. Before SKA-Mid is operating in steady state (AA4) a number of preparatory observations are needed, some of which have started, while others are not yet planned. With MeerKAT, observing programs are underway to observe the Zeeman effect in OH, starting with Orion B and including regions with bright OH lines (typically in absorption against HII regions). The survey of the Galactic plane in OH with ASKAP (GASKAP-OH; Dawson et al., 2024) is about to start its main program, which will provide

many new targets for OH Zeeman observations.

FAST has made progress in Zeeman observations using HINSA (Ching et al., 2022), but its northern sky coverage and lack of significant overlap with the sky visible to the SKA limits its utility for synergistic observations. GASKAP-HI (Dickey et al., 2013) will provide both a sample of traditional HI absorption (against HII regions) and HINSA candidates, for SKA-Mid Zeeman follow-up. As noted earlier, simulations are required to determine the extent to which HINSA is possible with the SKA-Mid. Surveys that include RRLs are also needed, and these may have to wait for proposed complementary surveys proposed for the SKA telescopes (see chapters by Karska et al. (2026), Salas et al. (2026), & Traficante et al. (2026)).

Our knowledge of the distribution and brightness of the other thermal tracers discussed earlier (CH, CCS, C₄H, SO) is extremely limited, particularly at SKA frequencies, and so surveys of these lines are needed before dedicating serious SKA time to Zeeman observations. As these are expected to be high-density tracers, targeted survey observations can be undertaken, for example of dense cores in star-forming regions in the Gould Belt and the Galactic Plane, as revealed by large-area (sub)mm/far-IR line and dust-continuum surveys with e.g., Planck, Herschel, APEX, Mopra, and the JCMT. These surveys can be undertaken with SKA-Mid AA* for CCS and C₄H, as no comparable facility will exist prior with sufficient sensitivity and frequency coverage for this undertaking. For CH at 700 MHz a targeted survey with ASKAP could be undertaken once the bulk of its current large programs are completed, or with SKA-Mid AA*.

Beyond the current SKA baseline (AA4), an increase in the frequency coverage to SKA-Mid above 15 GHz would give access to the CCS and H₂O lines at 22 GHz, and the C₄H lines at 19 GHz, while any increase in sensitivity will allow for new Zeeman effect detections. Being able to observe the Zeeman effect in both the 11 GHz and 22 GHz CCS lines would provide confirmation of a detection in either line. An increase in both angular resolution (VLBI baselines) and sensitivity for SKA-Mid would be advantageous for Zeeman effect observations with masers, enabling statistical studies of magnetic field strength throughout a significant volume of the Galaxy.

In summary, the combination of sensitivity, resolution, and frequency coverage offered by the SKA will enable the utilization of many Zeeman effect tracers for magnetic field studies in ways not possible with existing facilities. The ability to map regions both near and far over a wide range of densities and spatial scales will greatly advance our understanding the role of magnetic fields in star formation and molecular cloud evolution. Combining maps of individual sources and statistical results from large ensembles, with complementary observations on larger scales and lower densities with large single-dish telescopes, and using other techniques (§5), will be crucial to making progress in this difficult area. One key advantage of the SKA is its ability to match beams at different frequencies, as Zeeman observations represent an averaged result over both the telescope's angular resolution and the regions sampled by the tracer. For instance, even at the same angular resolution and position, Zeeman measurements using HI, OH, and CCS would trace magnetic fields in progressively denser regions from diffuse envelopes to dense cores along the line of sight. To disentangle these effects, chemical and radiative transfer modeling of multi-tracer Zeeman data from SKA and other telescopes will be essential to reconstruct the three-dimensional magnetic field within a source.

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