The magnetic field in the dense photodissociation region of DR 21

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ABSTRACT
Measuring interstellar magnetic fields is extremely important for understanding their role in different evolutionary stages of interstellar clouds and star formation. However, detecting the weak field is observationally challenging. We present measurements of the Zeeman effect in the 1665 and 1667 MHz (18 cm) lines of the hydroxyl radical (OH) lines towards the dense photodissociation region (PDR) associated with the compact H II region DR 21 (Main). From the OH 18 cm absorption, observed with the Karl G. Jansky Very Large Array, we find that the line-of-sight magnetic field in this region is \( \sim 0.13 \) mG. The same transitions in maser emission towards the neighbouring DR 21(OH) and W 75S-FR1 regions also exhibit the Zeeman splitting. Along with the OH data, we use [C II] 158 \( \mu \)m line and hydrogen radio recombination line data to constrain the physical conditions and the kinematics of the region. We find the OH column density to be \( \sim 3.6 \times 10^{16} (T_{\text{ex}}/25 \text{ K}) \) cm\(^{-2}\), and that the 1665 and 1667 MHz absorption lines are originating from the gas where OH and C\(^+\) are co-existing in the PDR. Under reasonable assumptions, we find the measured magnetic field strength for the PDR to be lower than the value expected from the commonly discussed density–magnetic field relation while the field strength values estimated from the maser emission are roughly consistent with the same. Finally, we compare the magnetic field energy density with the overall energetics of DR 21’s PDR and find that, in its current evolutionary stage, the magnetic field is not dynamically important.

Key words: ISM: H II regions – ISM: individual objects (DR21) – ISM: kinematics and dynamics – ISM: Magnetic fields – ISM: photodissociation region (PDR) – ISM: radio lines.

1 INTRODUCTION
The magnetic field, \( B \), is expected to play an important role in the dynamics of interstellar clouds in various stages of their evolution and in the formation of stars (for an overview, see Crutcher 2012). Currently, even while this is widely accepted as plausible, how and to what extent the magnetic field influences processes acting in the interstellar medium (ISM) are not entirely understood. Two strikingly different pictures have emerged, namely that of magnetically dominated star formation (e.g. Mouschovias 1991; Mouschovias & Ciolek 1999) and a turbulence-dominated star formation theory (e.g. Padoan & Nordlund 1999; Mac Low & Klessen 2004). While the debate is far from being settled, the tremendous progress in magnetohydrodynamic simulations in the last decade starts to show that answer lies somewhere in between (for an overview, see Hennebelle & Inutsuka 2019). Therefore, observational studies of the magnetic field strength in molecular clouds in different evolutionary stages are necessary. However, measuring the weak (\( \lesssim \)mG) interstellar magnetic field is challenging. Apart from the general issue that \( B \)-fields in the various components of the ISM are weak, different direct and indirect methods of estimating the magnetic field have their own limitations. For example, the rotation measure, resulting from the Faraday effect, only provides a line-of-sight (LOS) density-weighted integrated quantity and can only be measured for the ionized ISM. Imaging the linear polarization of the far-infrared or (sub)millimetre radiation of interstellar dust provides the direction of the \( B \)-field, but not its strength (Hildebrand 1988). Heiles & Havercorn (2012) give a summary of the various methods used for the measurement of magnetic fields in the different phases of the ISM.

Much of the molecular as well as the atomic neutral ISM of the Milky Way consists of photodissociation regions (PDRs) – regions in which both energetics and astro-chemistry are regulated by far-ultraviolet (FUV; \( \sim 6–13.6 \text{ eV} \)) photons. Apart from the rich ISM physics and chemistry involved, on a global scale, PDRs are directly related to the star–gas–star cycle via the formation and destruction of star-forming molecular clouds, and may play a role in regulating the star formation rate via FUV-induced feedback. Now, the two above-mentioned scenarios of star formation make distinct predictions for the spatial gradient of the mass-to-flux ratio (\( \frac{\mu}{\Phi_1} \)) between the core of a molecular cloud and its envelope. In ambipolar diffusion-driven fragmentation of magnetically dominated clouds, the quantity \( R \equiv \frac{\mu}{\Phi_1 \text{envelope}} \), i.e. the ratio of the mass-to-flux ratio of the core to that of the envelope, is always greater than 1 (e.g. Tassis & Mouschovias 2007). In turbulence-driven fragmentation, \( R \) can have a wide range of values not necessarily larger than 1 (e.g. Lunntila et al. 2009).
For this reason, magnetic field measurements to constrain the mass-to-magnetic flux in the core and the PDR envelope of star-forming regions are very promising in distinguishing between the theories for cloud fragmentation.

Zeeman splitting observations of spectral lines are an important tool to directly estimate (often only the LOS component of) the magnetic field in the region where the spectral line is originating from absorption or emission. There are various spectral lines, with reasonable Zeeman splitting factor, originating from different atomic and molecular species (for a compilation, see table 1 of Heiles et al. 1993). The target transition can be chosen depending on the nature of the source; these different species and their transitions trace a variety of physical conditions of the ISM. The goal is to relate the results of the magnetic field determinations to the density and temperature, as well as the morphology and kinematics of the sources in different evolutionary stages of interstellar clouds and star formation.

1.1 The OH radical and its Zeeman splitting

The hydroxyl radical (OH) is a tracer of different environments of the molecular ISM and well suited for magnetic field measurements (Crutcher & Kazes 1983). It is widespread in diffuse and translucent as well as dense, dusty interstellar clouds. OH is also found in the dense molecular envelopes of (ultra)compact H II regions (Guilloteau, Baudry & Walmsley 1985), where it forms via the photodissociation of H2O by UV radiation from the newly formed early-type stars (Elitzur & de Jong 1978; Hartquist & Sternberg 1991). In many of the younger ultracompact H II regions, OH lines from radio wavelength hyperfine structure (hfs) transitions from a variety of rotational levels show intense maser emission (strongest in the 1665 and 1667 MHz ground-state lines), with the archetypal W3(OH) being the prime example. Some of the lines arising from energy levels high above the ground state show (enhanced) absorption (Guilloteau 1982). In contrast, these lines exclusively show absorption towards more developed compact H II regions such as DR 21 (e.g. Matthews et al. 1986).

Due to A-doubling and hfs splitting, the ground-state rotational level of the OH +^1/2_3 spin variant splits into a quartet of lines with rest frequencies near ~1612, 1665, 1667, and 1720 MHz (Draine 2011). These lines are further subject to Zeeman splitting, and may be used to measure the magnetic field in molecular clouds where these lines are observed in emission and/or absorption. Please note, if the Zeeman splitting is smaller than the Doppler line width, then the spectral lines are highly blended. Unless the magnetic field is strong enough, such that the splitting is greater than the Doppler width, it is extremely difficult to directly detect the line splitting (Sault et al. 1990; Crutcher et al. 1993). However, as the components of the Zeeman splitting lines are circularly polarized in opposite senses (right and left hand), it is possible to detect the small difference by subtracting the two circular polarizations and looking for the signal in Stokes V. For a magnetic field with a component along the LOS, B_{LOS}, the relative frequency shift between the right and left circular polarization (LCP) is \delta \nu = \pm z |B_{LOS}|, where the Zeeman splitting factors, z, are 3.27 and 1.96 Hz \muG^{-1} for the two main lines at 1665 and 1667 MHz, respectively (Crutcher 1977; Kazes & Crutcher 1986). Hence, the Zeeman splitting measurements of these OH 18 cm lines allow for the estimation of the magnetic field, even in the relatively low density regime (Crutcher et al. 1993). On the other hand, OH maser emission arises in compact, high-density regions (n ~ 10^6 cm^{-3}), under special circumstances, and the maser lines can be utilized to estimate the field strength in such high-density regions. The density of the environment probed in this study, the PDR of DR 21 (Main), lies, at ~10^6 cm^{-3}, between the aforementioned values.

In this paper, we present observations of the DR 21 molecular cloud complex with the Karl G. Jansky Very Large Array (VLA). We study the Zeeman splitting of the OH 1665 and 1667 MHz lines seen in absorption towards the PDRs associated with the H II region DR 21 Main and estimate the magnetic field strength. We also briefly report on maser emission in these lines towards DR 21 (OH).

In Section 2, we present a brief overview of the relevant information about the DR 21 cloud. We present the details of the observations and data reduction in Section 3. In Section 4, we describe the method of estimating the magnetic field strength from the Zeeman splitting measurements of the 1665 and 1667 MHz transitions of OH and present our measurements. The results are presented and discussed in Section 5 that, to give context to our Zeeman effect determination, in Sections 5.1 and 5.2, summarizes the physical condition in the DR 21 (Main) PDR and its OH content. The OH absorption lines are used to estimate the OH column density (Section 5.3) and to understand the OH kinematics (Section 5.4), and, in Section 5.5 we compute the mass-to-magnetic flux ratio, and then compare magnetic, thermal, and hydrodynamical energy densities to understand the importance of magnetic field for the DR 21 (M) region. Finally, our main conclusions are summarized in Section 6.

2 DR 21

The DR 21 molecular cloud is a part of the Cygnus-X massive radio emission/molecular cloud complex, which hosts a large number of young massive stars ranging, in decreasing age, from several OB associations, over H II regions to even younger, deeply embedded objects (Reipurth & Schneider 2008). The DR 21 molecular cloud consists of a dense filament, which extends from the core associated with the compact H II region DR 21 (M) near its southern end to the ~3 arcmin (0.4 pc) more northern, younger, more deeply embedded DR 21 (OH) (also known as W 75S; Motte et al. 2007; Hennebmann et al. 2012). An overlay of the Herschel 70 \mu m image, 1.2 mm dust continuum emission from MAMBO (Motte et al. 2007; Hennebmann et al. 2012), and the OH 1665 MHz transition (VLA, this work) of this region, marking the location of DR 21 (M), DR 21 (OH), and W 75S, respectively, is shown in Fig. 1. DR 21 (OH) only shows quite weak radio emission (Argon, Reid & Menten 2000), but marks its activity with OH and also with class II CH3OH maser emission (Raimond & Eliasson 1969; Menten 1991). A few other cores in the filament also host maser sources (Motte et al. 2007). This cloud has been extensively studied at different wavelengths using various molecular tracers like CO, CN, HCN, SiO, CH3OH, HCO^+, OH, H2O, H2, H recombination line, etc., to name a few (e.g. Genzel & Downes 1977; Dickel, Dickel & Wilson 1978; Norris et al. 1982; Wendker 1984; Roelfsema, Goss & Geballe 1989; Garden, Russell & Burton 1990; Garden & Carlstrom 1992; Crutcher et al. 1999; White et al. 2010; Momjian & Sarma 2017; Dobashi et al. 2019). The intricate filamentary structures of this region have been mapped in emission from dust (Hennebmann et al. 2012), as well as using molecular lines (Schneider et al. 2010). By astrometric trigonometric parallax measurements of the 6.7 GHz CH3OH maser sources associated with DR 21, Rygl et al. (2012) have established its distance to be 1.50 kpc (to within 5 per cent accuracy). Extended mapping in lines of the ^13CO and ^12CO molecules by Dickel et al. (1978) and Dobashi et al. (2019) reveals two major kinematically distinct molecular cloud components, namely the main filamentary DR 21 cloud at v_{LSR} ~ -3 km s^{-1} with a mass of...
intermediate-velocity gas is also detected. Dickel et al. (1978) suggest the faint, compact H II region W 75 N lies within it (Dickel et al. 1978).

In this study, we probe, with OH absorption lines, the magnetic field and kinematics in the PDR that forms the interface between the compact H II region DR 21 M and its cooler molecular envelope and compare our findings with earlier results obtained from different tracers.

3 OBSERVATION AND DATA ANALYSIS

In Section 3.1, we detail the observational aspects of the OH 18 cm data presented in this work, observed using the VLA. In addition, we compare our 18 cm OH spectra with spectra of the 158 µm transition of ionized carbon and H 72α radio recombination line. The acquisition of the auxiliary data is briefly discussed in Sections 3.2 and 3.3.

3.1 Radio wavelength 18 cm data

The primary data for this work are taken from the data archive of the VLA. The observations were carried out over seven observing runs in 2014 July and August as part of the regular proposal VLA/14A-031. The main observational parameters are summarized in Table 1. For these observations, 3C 286 and 3C 138 were used as flux, delay, and bandpass calibrators, and J2052+3635 was used as the phase calibrator. The phase calibrator was observed for ~1.2 min for every ~9.8 min scan of the target source. Initial flagging and calibration are carried out using the scripted CASA (Common Astronomy Software Applications package) pipeline of the National Radio Astronomical Observatory (NRAO),2 with CASA version 4.7.2 and pipeline version 1.3.11, modified suitably for spectral line analysis. We have restricted our analysis to the two spectral line windows centred at the 1665 and 1667 MHz lines of OH. Flagging, calibration, and imaging for the two spectral windows are done entirely independently. For some observations, additional iterative manual flagging of the data and calibration was found to be required. Data from the ‘line free’ channels are combined to produce the continuum visibility data. Interactive imaging and deconvolution of the continuum data are done using the task clean to produce the continuum image. Here, uniform weighting (Brigg’s robust parameter = −2 in clean) of the visibility data is found to produce a marginally better image over the natural weighting. Standard self-calibration procedure is also applied to improve the calibration and image quality. Initial calibration, imaging, and self-calibration is done separately on data from each day’s observations before combining the calibrated data sets, and final continuum imaging. Similarly, continuum subtraction is done in the visibility domain from each day’s data using the CASA

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Table 1. Summary of observational parameters.

| Parameter                              | Value                              |
|----------------------------------------|------------------------------------|
| VLA proposal ID                        | 14A-031                            |
| Date of observations                   | 2014 July 7–August 19               |
| Configuration                          | D                                  |
| Observing band                         | L (1–2 GHz)                        |
| R.A. of field centre (J2000)           | 20°39′01″0"                         |
| Dec. of field centre (J2000)           | +42°19′43"                         |
| Calibrators                            | 3C 286, 3C 138, J2052+3635          |
| Continuum:                             |                                    |
| Observing bandwidth                    | 8 × 128 MHz                        |
| Number of channels                     | 8 × 64                             |
| Spectral line:                         |                                    |
| Rest frequencies                       | 1665.40 and 1667.36 MHz             |
| Observing bandwidth                    | 2 × 1 MHz                          |
| Number of channels                     | 2 × 1024                           |
| Channel spacing                        | 0.175 (km s\(^{-1}\))              |
| Primary beam (HPBW)                    | ~30 arcmin                         |
| Synthesized beam FWHM                  | ~33 arcsec × 28 arcsec             |
| On-source time                         | ~7 h 50 min                        |
| RMS noise (per channel)                | ~10 mJy per beam                   |

3.1.3 Radio wavelength 18 cm data

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1The +9 km s\(^{-1}\) cloud is sometimes termed as the ‘W 75 N cloud’, because the faint, compact H II region W 75 N lies within it (Dickel et al. 1978).

2The NRAO is operated by Associated Universities Inc., under a collaborative agreement with the US National Science Foundation.
A. Koley et al.

4828

Figure 2. Left: Integrated intensity map \([-86, +75] \text{ km s}^{-1}\) of the OH 1665 MHz absorption [towards DR 21 (M); white rectangle] and maser emission [towards DR 21 (OH) and W 75-FR1]. The regions towards which maser emission is detected are marked by the black and white circles that correspond to the positions of DR 21 (OH) \((\alpha = 20h39m01.57, \delta = +42^\circ22'45.74')\) and W 75S-FR1 \((\alpha = 20h38m59.99, \delta = +42^\circ24'35.67')\), respectively. Right: Zoomed-in view of the DR 21 (M) region showing the marginally resolved continuum emission by dashed black contours (contour levels: 1.24, 2.48, 3.73, and 4.97 Jy per beam), along with the integrated absorption in greyscale. The three different coloured circles mark the positions from where optical depth spectra are taken from, for comparison.

3.2 Ionized carbon line data

The study of Ossenkopf et al. (2010) presented, a.o., spectra of the 158 \(\mu\)m \(^2\)P\(_{3/2}\)–\(^2\)P\(_{1/2}\) fine structure line of ionized carbon \(\text{C}^+\) (rest frequency 1900.547 GHz) observed towards DR 21 with the Heterodyne Instrument for the Far-Infrared (HIFI) aboard the Herschel Space Observatory. For details, see Ossenkopf et al. (2010). A data cube of spectra mapped around DR 21, kindly provided by V. Ossenkopf-Okada, was used to generate the spectrum used in Fig. 3 with an effective resolution of 40 arcsec, not too different in size from that of the restoring beam of our VLA data (33 arcsec \(\times\) 28 arcsec).

3.3 Hydrogen radio recombination line data

In the framework of a larger scale project, we observed the H 72\(\alpha\) hydrogen recombination line (HRRL) towards DR 21 with the 100-m telescope at Effelsberg, Germany.\(^3\) The observations were carried out in position-switching mode with the S20mm receiver on 2019 August 23 (project id: 08-19). The S20mm receiver is a double-beam and dual-polarization receiver operating in the 12–18 GHz range that has, at 17.258 22 GHz, the frequency of the H 72\(\alpha\) RRL, an HPBW of 42 arcsec, similar to that of our VLA and Herschel/HIFI data. The spectrum was analysed with the facility Fourier transform

\(^3\)The 100-m telescope at Effelsberg is operated by the Max-Planck-Institut für Radioastronomie (MPIfR) on behalf of the Max-Planck Gesellschaft (MPG).
spectrometer. NGC 7027 was used as the absolute flux calibrator, and the flux calibration accuracy is estimated to be within \( \sim 10 \) per cent.

4 RESULTS: MAGNETIC FIELD ESTIMATION

Magnetic field in molecular clouds splits each of the OH rotational lines into three lines. Now, if the splitting exceeds the line width, and three distinct lines are detectable, then, from the line separations and line ratios for different polarizations, one can estimate the magnetic field strength \( (\mathbf{B}) \) as well as the field orientation \( (\theta) \) with respect to the LOS. However, even for narrow maser lines, due to Faraday depolarization in the emission region, all three lines are rarely detectable (see e.g. Sault et al. 1990, and references therein). On the other hand, if the magnetic field is weak, the splitting, in general, is smaller than the Doppler width. In this case, from the observed circular polarization, it is possible to measure only the LOS component of the magnetic field \( (B_{\text{LOS}} = B \cos \theta) \). Here also, the linearly polarized signal (Stokes Q and U) can, in principle, be used to derive the magnetic field component on the plane of sky (i.e. \( B \sin \theta \)) as well as the position angle \( (\chi) \). However, for small splitting, Q and U depend on the second derivative of specific intensity \( (I_v) \) with respect to \( v \). Thus, the current instrumental sensitivity is not high enough to obtain full three-dimensional magnetic field structure from the Zeeman splitting measurements (Sault et al. 1990; Crutcher et al. 1993). There are few complementary methods (e.g. measurement of dust polarization, the ion-to-neutral line width ratio, or estimating non-thermal broadening) that provide the full information under certain assumptions (see Houde et al. 2000a, b; Crutcher 2004; Roy, Peeddakkandy & Chengalur 2008; Crutcher 2012; Heiles & Havercorn 2012; Balser et al. 2016; Cho & Yoo 2016; Koley & Roy 2019). Alternatively, one may also use Bayesian analysis for a large number of observations to draw statistical inference (e.g. Crutcher 1999; Crutcher et al. 2010).

For the prevalent astrophysical scenario, where the splitting is small compared to the line width, the circular polarization profile (Stokes V spectrum) is proportional to \( B_{\text{LOS}} \) and the derivative of the intensity profile (Stokes I spectrum), giving rise to the characteristic ‘S’-shaped signature in the Stokes V profile (as the unshifted intensity profile (Stokes I spectrum), giving rise to the characteristic ‘S’-shaped signature in the Stokes V profile, but the uncertainty in the magnetic field estimated from each of the transitions is larger (see Table 3). In addition to the ‘S’-shaped signal, we also note the presence of a feature in the Stokes V spectrum of the 1665 MHz transition at \( v_{\text{LSR}} \sim 0 \)–\( 2 \) km s\(^{-1}\), which is likely to be due to residuals from the deconvolution and subtraction of the strong emission from the DR 21 (OH) maser site (see Appendix A for details). This velocity range is not included for estimating the magnetic field strength. Note that this feature is absent in the 1667 MHz Stokes V spectrum. Moreover, the ‘S’-shaped signal seen in the 1667 MHz Stokes V spectrum gives magnetic field strength that is consistent with that obtained from the 1665 MHz spectrum, making the measurements reliable.

We have detected OH maser lines towards previously known maser sites DR 21 (OH) and W 75S-FR1 (see Appendix A for details). Using these OH maser lines, as well as the absorption lines towards DR 21 (OH), we also critically checked if the ‘beam squint’, the relative offset between the primary beam patterns in both polarizations, significantly affects the results. The velocity gradient of the spectral line signal across the field along with beam squint may create a false Zeeman-like pattern (e.g. Crutcher et al. 1993). However, this effect is expected to be identical for both the 1665 and 1667 MHz lines, whereas for real Zeeman pattern, the splitting ratio is 5/3 for the two lines. We do not see such an identical shift to both the lines, a telltale sign of beam squint effect, in the maser and the absorption spectra. Hence, we expect that the signal we observe is due to true Zeeman splitting, and not an artefact due to beam squint.
temperatures, distance from the UV illuminating source, and mass to comprise of broadly two ensembles of clumps differing in their gas velocity as the OH and the \([\text{C II}]\) lines and is centred on a somewhat which on the low-velocity (blueshifted) side extends to a similar which we image the OH absorption (N46 and N47, respectively, in their nomenclature). The OH-bearing gas is expected to reside in the partially ionized interface region between the central \(\text{H II}\) region and the general ISM.

The OH-bearing gas is expected to reside in the partially ionized interface region between the central \(\text{H II}\) region and the general neutral gas, i.e. in a PDR. This is also quite evident from the comparison of the \(\text{Herschel HiFI}\) 158 \(\mu\text{m} \ [\text{C II}]\) emission spectrum with the OH 1665 and 1667 MHz absorption spectra. As \(\text{C}^+\) is the prime tracer of PDRs, the similarity of the line profiles strongly indicates that the 1665 and 1667 MHz lines are originating from OH coexisting with \(\text{C}^+\) in the PDR.

In Fig. 3, we also show the spectrum of the H 72\(\alpha\) RRL. It displays a quite symmetric broad profile covering \((-45)\)\,--\,(+50) km s\(^{-1}\), which on the low-velocity (blueshifted) side extends to a similar velocity as the OH and the \([\text{C II}]\) lines and is centred on a somewhat higher value than the systemic velocity of DR 21's molecular cloud, defined by (sub)mm-wavelength molecular lines, which is between \(-3\) and \(-1\) km s\(^{-1}\). For example, the 345 GHz CO \(J = 3\)–\(2\) has a complex multipeaked spectrum covering \((-25)\)\,--\,(+20) km s\(^{-1}\), i.e. a narrower range than the HRRL's but centred on the systemic LSR velocity (Ossenkopf et al. 2010). In contrast, the intensity of the OH absorption and also that of the \([\text{C II}]\) emission is very much diminished at (redshifted) velocities higher than the systemic value.

For OH, this finding has a natural explanation in the fact that the RRL traces all the ionizing material of the expanding DR 21 compact \(\text{H II}\) region, while on the other hand, OH in absorption can naturally only be observed from the part of the also expanding PDR that is moving towards the observer and thus blueshifted. The \([\text{C II}]\) line also has an asymmetric profile with a marked intensity drop between LSR velocities of \(-7\) and 16 km s\(^{-1}\). Absorption in the lower part of this range corresponds to the extended \(^\sim\) W 75 N 9 km s\(^{-1}\) cloud discussed in Section 2. We also see absorption in both OH lines in this velocity range. This is expected for both species, as \(\text{C}^+\) and OH trace PDRs as well as the general ISM.

It is instructive to compare the \([\text{C II}]\) line’s profile with the profiles of emission lines from simple molecules. In their fig. 4, Schneider et al. (2010) present profiles of lines from the low-density tracing molecules \(^{12}\text{CO}\) and \(^{13}\text{CO}\) and the higher density tracing HCO\(^+\) averaged over the DR 21 filament and ascribe LSR velocity ranges to various kinematic components. Generally, these profiles are centred on DR 21's systemic LSR velocity (\(-2.6\) km s\(^{-1}\)). In addition, a W 75 N 9 km s\(^{-1}\) cloud component is observed between 5 and 11 km s\(^{-1}\) in emission from the low-critical density \(^{12}\text{CO}\) and \(^{13}\text{CO} J = 2\)–\(1\) lines, while in the HCO\(^+\) 1–0 line an absorption dip is observed in that velocity range. This is exactly what one might expect, as the HCO\(^+\) line, like the \([\text{C II}]\) line (which is also self-absorbed at these velocities), has a significantly higher critical density than the carbon monoxide lines.

### 5 DISCUSSION

#### 5.1 Gas and dust in DR 21’s PDR

In recent years, with the aid of velocity-resolved observations of the fine structure lines of atomic carbon \(\text{C I}\) \((^3\text{P}_1–^3\text{P}_0\) and \(^3\text{P}_2–^3\text{P}_1)\), \([\text{C}^+]\), and high-\(J\) transitions of CO, \(^{13}\text{CO}\), and HCO\(^+\) using HiFI/Herschel, the PDR structure of the DR 21 region has been more accurately modelled. Ossenkopf et al. (2010) have modelled this region using the KOSMA-\(\mu\) PDR model assuming the DR 21 region to comprise of broadly two ensembles of clumps differing in their gas temperatures, distance from the UV illuminating source, and mass fraction. The hotter clumps lie closer to the inner \(\text{H II}\) region with only a small contribution towards the total mass fraction while the bulk of the material is comprised of the cooler clumps. Combined, with the observations, the best-fitting models result in gas densities between \((1.1–1.3) \times 10^6 \text{ cm}^{-3}\) for the cold and hot components, respectively. This estimate is supported by the \(^2\text{H}_2\) densities of \((9.1 \times 10^5\) and \((1.9 \times 10^6 \text{ cm}^{-3}\) that Motte et al. (2007) derive from (sub)mm continuum data for the two clumps associated with the cm emission from DR 21's \(\text{H II}\) region that are located within the area towards which we image the OH absorption (N46 and N47, respectively, in their nomenclature).

For OH, the estimated number of OH absorption lines from a variety of rotational states, Jones et al. (1994) found the number density of the OH bearing gas, specifically for DR 21 (M), to be \(n_{\text{OH}} = (1.8 \pm 0.7) \times 10^7 \text{ cm}^{-3}\). These authors derive a similar value for the OH abundance of...
A plausible number for the H$_2$ density of the OH-bearing gas. Interferometry (VLBI) data of the 1665 and 1667 MHz OH lines, current measurement, as well as various other entries, falls below 0.13 mG, for our assumed H$_2$ density of 10$^6$ cm$^{-3}$, bringing this into context our findings, in Fig. 5 we plot our data point, $k$ absolute values between 150 and 500 K, broadening of the carbon RRLs, an indirect method for which are supported by a variety of data and we adopt 10$^6$ cm$^{-3}$ as an order magnitude higher than the values discussed in Section 5.1, temperatures, respectively. A caveat would be that the collisional rate coefficients recently presented by Kłos et al. (2020).

Returning to our $B$-field measurement, ours is the first direct measurement of the magnetic field strength in the dense PDR associated with DR 21 (M) using OH thermal absorption at 1665 and 1667 MHz and one of the few such measurements in any PDR. Earlier, Troland et al. (2016) observed the Orion’s veil, a dilute PDR associated with the Orion Nebula and measured magnetic fields $\sim$50–75 $\mu$G in the atomic gas, but as high as $\sim$350 $\mu$G in molecular gas using the OH 1665 and 1667 MHz transitions. Additionally, using Zeeman detections of the OH 1665 MHz line towards the central PDR of the M17 H II region/giant molecular complex, Brogan & Troland (2001) measured the LOS component of the magnetic field to have absolute values between 150 and 500 $\mu$G.

Balser et al. (2016) also reported total field strength ($B_{\text{TOT}}$) of the order of 100–1000 $\mu$G for PDRs, inferred from the non-thermal broadening of the carbon RRLs, an indirect method for $B$-field determinations. It appears to be well established that over many orders of magnitude of the gas density, $n$, the absolute value of the magnetic field strength, $|B_{\text{TOT}}|$, is proportional to $n^k$, where the power-law index, $k$, has a value of 0.65 (Crutcher et al. 2010). To bring this into context our findings, in Fig. 5 we plot our data point, 0.13 mG, for our assumed H$_2$ density of 10$^6$ cm$^{-3}$. As expected, the current measurement, as well as various other entries, falls below the envelope representing the above power-law relation.

Fish & Reid (2006) analyse and interpret their very long baseline interferometry (VLBI) data of the 1665 and 1667 MHz OH lines for the 18 high-mass star-forming regions that were presented in Fish et al. (2005). Their conclusions regarding $B$-field strengths are illustrated in Fig. 5 and discussed in our Appendix A, in particular for DR 21 (OH). They find a total of 184 Zeeman pairs almost all of which indicate $B$-field strengths between <1 and 8 mG, with 5 outriggers having higher values. Employing the $B$ versus $n$ relationship described above (but with a power-law index of 0.5), Fish & Reid (2006) infer densities corresponding to these $B$-fields, deriving values between $<10^5$ and $10^7$ cm$^{-3}$. In principle, the calculations reported by Cesaroni & Walmsley (1991) and Gray, Doel & Field (1991) allow for inversion over this range of densities, while values at the higher end of this range are more probable. Higher densities would be expected if the masers arose from special, localized high-density regions embedded in a lower density OH-rich environment. Indeed, for the OH maser emission in 18 high-mass star-forming regions they mapped with VLBI, Fish & Reid (2006) report a universal clustering scale for the maser spots of only 10$^{15}$ cm [44 mas at DR 21 (OH)]. From the observational side, such scales are difficult to access by observations of thermally excited lines, even in the era of powerful interferometers. Clearly, a detailed excitation/radiative transfer study of the physical conditions in OH-bearing environments of (ultra)compact H II regions would be highly desirable that would utilize the newly calculated hfs-resolved collision rate coefficients recently presented by Klos et al. (2020).

5.3 OH column density and excitation

From the 1665 and 1667 MHz absorption lines, the OH column density can be determined using the relation

$$N_{\text{OH}}/T_{\text{ex}} = C \int \tau \, dv \, \text{cm}^{-2} \text{K}^{-1},$$

where $T_{\text{ex}}$ is the excitation temperature (in K) of the respective OH transitions, $\text{dv}$ is in km s$^{-1}$, and the value of the constant $C$ is 4.1063 \times 10^{14} and 2.2785 \times 10^{14} cm^{-2} \text{ (km s}^{-1}) K^{-1}$ for the OH 1665 and 1667 MHz lines, respectively (Roberts, Crutcher & Troland 1995; Sarma et al. 2000). In principle, a joint absorption/emission study could provide the excitation temperature. As we have no emission data for DR 21, we resort to the literature for information on $T_{\text{ex}}$. Strong maser emission in the 1665/1667 MHz OH lines is an archetypal signpost for ultracompact H II regions, with W3(OH) the first source identified as such (Mezger et al. 1967). In addition to the ground-state lines, many hfs lines from rotationally excited levels also are masing, while others show (enhanced) absorption (Cesaroni & Walmsley 1991). In the material around more evolved compact H II regions such as DR 21, the physical conditions no longer support maser action and absorption prevails. Radiative transfer model calculations using such multitransition observational data as constraints, such as those of Jones et al. (1994; see Section 5.2), can be used to constrain the physical conditions in OH-bearing regions. Unfortunately, that study gives no information of $T_{\text{ex}}$ values predicted by their models. In contrast, the extensive study of Cesaroni & Walmsley (1991) does present, in its table 2, $T_{\text{ex}}$ values for a fixed $n_{\text{H}_2} = 10^7$ cm$^{-3}$ (close to the value we derived above for DR 21) and a wide range of OH column densities from $5 \times 10^{13}$ cm$^{-3}$ to $1.6 \times 10^{17}$ cm$^{-3}$. Except for the lowest and highest values, they find $T_{\text{ex}}$ to be negative, i.e. inversion, for the 1665 and 1667 MHz lines. For these lines, they derive $T_{\text{ex}} = 7.7$ and 32.3 K, values that are diametrically opposite from those found in an earlier study by Guillemot et al. (1985), 32.5 and 8.7, respectively. Given the obvious uncertainties of such estimates, in our case we assume a fiducial value of $T_{\text{ex}} = 25$ K to calculate the column densities reported for the different velocity components in Table 2. This yields column densities in the range of $\sim 10^{14}$–$10^{16}$ cm$^{-2}$, lower than the value Cesaroni & Walmsley (1991) quoted above. This is hardly surprising given all the uncertainties and the fact that local thermodynamic...
have not been able to study if there is any clear systematic variation however, due to the coarser angular resolution of our observations, we in Fig. 6. The details of the multi-Gaussian fit parameters are modelling of the optical depth profile of the OH spectra as shown broad negative velocity wing, are evident from the multi-Gaussian and one moderately broad components at positive velocities, and a broad components at negative velocities, three narrow components prominent components, namely two narrow and two moderately line data in terms of the optical depth, following equation (3). As & Simon 1980; Roberts et al. 1997) with variation of central velocity emerging from the embedded protostar (e.g. Fischer, Righini-Cohen & Carlstrom 1992). Garden et al. (1991) estimated the mass of the outflow to be $>3000 M_\odot$ and energy $>2 \times 10^{48}$ erg, one of the most energetic outflows observed in such systems. Garden et al. (1990) and Garden & Carlstrom (1992) have also reported hot ammonia and H$_2$O maser near the origin of the outflow (an infrared star I6), and equilibrium, which is a premise for the applicability of equation (2), is clearly not a valid concept for OH in the regions in question.

### 5.4 OH kinematics

Earlier, Cyganowski et al. (2003) and Immer et al. (2014) carried out comprehensive studies of the DR 21 (M) region using radio continuum, molecular tracers as well as radio recombination lines, with detailed discussion on champagne flow versus bow shock model for the H II region continuum. General radiative transfer for OH absorption in the presence of the Galactic isotropic and discrete source background is discussed in Goss (1968). Typically, when the discrete source is the dominant background, the radiative transfer equation (Roberts, Dickel & Goss 1997) becomes

$$1 + \frac{T_b(v)}{T_c} = e^{-\tau(v)}, \quad (3)$$

where $T_b(v)$ and $T_c$ are the continuum-subtracted brightness temperature of the absorption line and the continuum temperature, respectively. The CASA task `immath` is used to convert the spectral line data in terms of the optical depth, following equation (3). As an example, the OH 1667 MHz optical depth profile is shown in Fig. 6 towards the region where the magnetic field is detected. Nine prominent components, namely two narrow and two moderately broad components at negative velocities, three narrow components and one moderately broad components at positive velocities, and a broad negative velocity wing, are evident from the multi-Gaussian modelling of the optical depth profile of the OH spectra as shown in Fig. 6. The details of the multi-Gaussian fit parameters are summarized in Table 2. There is some variation of the optical depth across the background continuum region as shown in Appendix B; however, due to the coarser angular resolution of our observations, we have not been able to study if there is any clear systematic variation of the central velocities of these different components.

Previous high-resolution (5 arcsec) H I and CO observations attributed this negative velocity wing to an outflow component emerging from the embedded protostar (e.g. Fischer, Righini-Cohen & Simon 1980; Roberts et al. 1997) with variation of central velocity along the outflow axis (NE–SW on the plane of the sky; Garden & Carlstrom 1992). Garden et al. (1991) estimated the mass of the outflow to be $>3000 M_\odot$ and energy $>2 \times 10^{48}$ erg, one of the most energetic outflows observed in such systems. Garden et al. (1990) and Garden & Carlstrom (1992) have also reported hot ammonia and H$_2$O maser near the origin of the outflow (an infrared star I6), and

![Figure 6.](https://academic.oup.com/mnras/article-lookup/doi/10.1093/mnras/stab164)
density with the thermal and hydrodynamic energy density. For thermal energy density ($u_{\text{th}} = 3/2P_{\text{th}} = 3/2nk_{\text{B}}T$), kinetic temperature is assumed to be $T_{\text{ex}}$, and typical $n(H_2) \sim 10^5$ cm$^{-3}$ in the this PDR region, this results in an energy density of $u_{\text{th}} = 5.17 \times 10^{-9}$ dyn cm$^{-2}$ $(3.23 \times 10^8$ eV cm$^{-3}$). For simplicity, we have assumed the velocity dispersion to be isotropic, and the hydrodynamic energy density ($u_{\text{hydro}} = 1/2\rho v^2$) is estimated to be $\sim 9 \times 10^{-8}$ dyn cm$^{-2}$ $(\sim 5.7 \times 10^4$ eV cm$^{-3}$). The magnetic field energy density ($u_B = B^2/8\pi$), on the other hand, is 0.67, 2.69, and $22.3 \times 10^{-9}$ dyn cm$^{-2}$ (0.42, 1.68, and 13.9 keV cm$^{-3}$) for a magnetic field orientation of $\theta = 0^\circ$, 60$^\circ$, and 80$^\circ$ with respect to the LOS, respectively. Note that the various energy densities are computed only for the narrow-line component for which the magnetic field value has been measured from the OH Zeeman splitting as in Table 2. For the $\theta = 0^\circ$, 60$^\circ$, and 80$^\circ$ scenarios, the ratios of thermal to magnetic pressure (similar to ‘plasma $\beta$’ parameter in highly ionized medium) are $\sim 5.1, 1.3$, and 0.2, respectively.

Another important parameter to consider is the mass-to-flux ratio based on our estimated magnetic field value. The mass-to-flux ratio over its critical value (Nakano 1978) is given by

$$\lambda_c = \frac{(M/\Phi_{\text{obs}})}{(M/\Phi_{\text{critical}})} = 7.6 \times 10^{-21} \frac{N(H_2)}{B_{\text{total}}},$$

where $N(H_2)$ is in cm$^{-2}$, $B_{\text{total}}$ is in $\mu$G, and $(M/\Phi)_{\text{critical}} = 1/\sqrt{4\pi^2}$ (also see Tomisaka 1998; Krumholz 2011, for a discussion on critical mass-to-flux ratio). Using an OH abundance of $\sim 10^{-7}$ (Jones et al. 1994), we derive an $H_2$ column density for the narrow component of $\sim 1.1 \times 10^{23}$ cm$^{-2}$. Thus, the normalized mass-to-flux ratio values are 6.6, 3.4, and 1.11 for $\theta = 0^\circ$, 60$^\circ$, 80$^\circ$, respectively. Clearly, with these reasonable assumptions, $\lambda_c > 1$, for all possible orientations. So, from these results we can clearly say that we are probing a magnetically supercritical envelope region, where the magnetic field is not dynamically important. This is consistent with magnetohydrodynamic simulations that show that while magnetic field might suppress small-scale fragmentation, it may have little influence on the expansion of the $H_2$ region itself (e.g. Arthur et al. 2011).

Despite these attainable calculations showing the relative importance of magnetic fields in molecular clouds, many more such observations and theoretical studies (see e.g. Mouschovias & Tassis 2009; Tritis et al. 2015) are necessary to address and resolve the questions at hand. In addition, further deeper and higher resolution observations of the DR 21 region will be useful in order to detect (or put tight constraints) the magnetic fields associated with the other components, as well as to carry out spatially resolved estimations of the magnetic field. This will allow us to better understand the field geometry as well as probe the density dependence of the magnetic field in different parts, and thus test various theoretical predictions.

**6 CONCLUSIONS**

We have presented data on the 1665 and 1667 MHz transitions of OH, in absorption towards DR 21 (M) and showing maser emission in the neighbouring DR 21 (OH) and W 75S-FR1 regions. Our observations and analysis reveal the following:

(i) We determine an LOS magnetic field strength of $130 \pm 16$ $\mu$G towards the PDR associated with the DR 21 (M) region.

(ii) Our observations of OH absorption, a hydrogen RRL, and the [C II] 158 $\mu$m line (the quintessential tracer of PDRs) all are consistent with the scenario that OH is co-existing with $C^+$ in the PDR, whereas the RRL traces the ionized gas in the compact, expanding H II region. The asymmetry in the [C II] line is due to absorption from the $W$ 75 N 9 km s$^{-1}$ component.

(iii) In addition to the narrow and moderate components, we detect one negative velocity wing (FWHM $\sim 24$ km s$^{-1}$), possibly associated with the prominent DR 21 bipolar outflow.

(iv) The estimated OH column densities for the various components are in the range from $\sim 10^{15}$ to $10^{16}$ cm$^{-2}$ towards the PDR surrounding the compact H II region of DR 21 (M), and the total column density is estimated to be $\sim 3.6 \times 10^{16}$($T_{\text{ex}}/25$ K)$^{-1}$ cm$^{-2}$ with significant uncertainty due to the lack of any tight constraint on $T_{\text{ex}}$.

(v) We also detect both 1665 and 1667 MHz OH masers towards DR 21 (OH), and only 1665 MHz masers for W 75S-FR1.

(vi) We calculate energy densities and mass-to-flux ratio for DR 21 (M) under some reasonable assumptions, and show that the thermal, hydrodynamical, and gravitational energy densities dominate over magnetic energy density.

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**DATA AVAILABILITY**

The data products from this study will be shared on reasonable request to the corresponding author.

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APPENDIX A: DR 21 (OH) MASER EMISSION

In addition to the OH absorption lines towards DR 21 (M), we also detect the OH 1665 and 1667 MHz maser lines towards previously known maser sites DR 21 (OH) and W 75S-FR1 that were also covered by our imaging (see Fig. 2). For the W 75S-FR1 region, only the 1665 MHz maser line is detected. The observed spectra are shown in Figs A1–A3. These narrow, bright and variable maser lines originate in high-density compact regions. As mentioned earlier, full spectral-polarimetric VLBI observations of these lines are required to measure the magnetic fields as well as the velocity structures and dynamical evolution of these small (∼100 au sized) compact regions. This, however, necessitates high-spatial resolution observations to disentangle emission from multiple maser spots in the same region at slightly different velocities. As even its name says, DR 21(OH) is a classic OH maser region. Recently relative studies of the 1665 and 1667 MHz OH hfs lines by Argon et al. (2000) and Fish et al. (2003, 2005) with the VLA and the Very Long Baseline Array (VLBA) show a velocity range of the emission comparable to that observed by us (see further below). The Zeeman splitting factors quoted in Section 1 correspond to 0.59 and for the 1665 and 1667 MHz lines, respectively. With the few mG fields in maser regions, this causes differences of the RCP and LCP signals of the order of a few km s⁻¹. As first pointed out by Cook (1966), given the velocity structure and turbulence in maser clumps, this can affect the gain paths for the RCP and LCP signals differently, which may result in very different intensities. This makes B-field determinations based on single-dish measurements of the 18 cm OH lines very uncertain or impossible. On the other hand, very reliable field measurements are possible if VLBI data are available, which yield sub-milliarcsecond accuracy for maser spot positions and RCP to LCP registration accuracy (Fish et al. 2005). A field can be determined if RCP and LCP components appear at the same position in the sky. For DR 21(OH), Fish et al. (2005) find...
Magnetic field in DR 21

Figure A1. Left: OH 1665 MHz maser lines at the position of DR 21 (OH) from the present VLA data. The Stokes LCP and RCP components are represented by the solid blue and dashed red lines, respectively. Right: Equivalent spectra observed using the VLBA at an earlier epoch, reconstructed from parameters given in Fish et al. (2005). Both sets of spectra show a good correspondence between the distributions of velocity components but show variability in their amplitude.

Figure A2. Same as Fig. A1 but for the OH 1667 MHz line.

Figure A3. OH 1665 MHz maser spectra at the position of W 75S-FR1 in right and left circular polarization. The corresponding 1667 MHz transition is not detected at this location.

Of course, the data presented here, observed with the VLA in D configuration, do not offer adequate angular resolution to separate the maser spots. As a consistency check, we compare the observed spectra resulting from our observations with the reconstructed VLBA spectra based on published parameters taken from Fish et al. (2005). While this serves as a qualitative check for consistency, a one-to-one comparison of the velocity components does not make sense. In spite of that, Fig. A1 shows very good agreement of the central $v_{\text{LSR}}$ of different components (in both polarizations), and significant variation of relative amplitudes for the 1665 MHz maser lines. For the 1667 MHz lines also, as shown in Fig. A2, we see variability.

three clusters of maser spots separated by 1.5 arcsec (2200 au) from each other, each containing several components for some of which they determine $B$-field strengths. They find values of $(-5.3)$–$(-3.8)$, $-7.6$, and $(+5.6)$–$(+6.6)$ mG, respectively, indicating a field reversal. We include the above-mentioned field strengths in Fig. 5 and our discussion in Section 5.2. We note that these field strengths are an order of magnitude higher than the values determined for two dense molecular cores in DR 21 (OH) discussed in Section 2, again indicating significantly enhanced densities in maser-emitting clumps.
a much lower intensity of the prominent 2.25 km s$^{-1}$ RCP component in our VLA spectrum; a few of our components are not reported in Fish et al. (2005].

APPENDIX B: OH OPTICAL DEPTH SPECTRA IN DIFFERENT REGIONS

The OH optical depth spectra in different parts of the DR 21 (M) region have slight variation. In Fig. 2, three positions, namely the peak of the continuum, the position corresponding to the most significant OH Zeeman splitting detection (roughly coinciding with the Herschel 70 μm peak shown in Fig. 1) on the right, and an offset position on the left, are marked in red, green, and white, respectively. We show, in Fig. B1, the OH 1667 MHz optical depth spectra of the corresponding positions in red, green, and blue, respectively. Apart from the slight variation of the peak optical depth, the spectra are consistent with one another. Careful multi-Gaussian decomposition of both the 1665 and 1667 MHz spectra shows only a weak indication of variation of the central velocity of the negative velocity wing (outflowing component). However, we are severely limited by the coarse angular resolution of the present observations, and high-resolution observation will be valuable to probe any possible systematic variation of the velocity of these different components across the region.

![Figure B1. OH 1667 MHz optical depth profile towards the three DR 21 (M) positions (also marked in Fig. 2), namely towards the peak of the continuum emission (in red), the region where the magnetic field is significantly detected (in green), and an offset position towards the left of the continuum peak (in blue).](https://academic.oup.com/mnras/article-lookup/doi/10.1093/mnras/stab2528)