Magnetic fields in dark cloud cores and H_2O masers

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ABSTRACT. We present results of recent circular polarization experiments with the MPIfR 100-m telescope, revealing for the first time, the magnetic field strength towards interstellar H_2O masers and the dense cores of local dark cloud complexes. Weak Zeeman splittings of a few 10 kHz only in the 22.235 GHz maser transition of the non-paramagnetic H_2O molecule imply magnetic field strengths of ~ 50 mG in the dense ($n \sim 10^{10}\,cm^{-3}$) masing layer. With the recently identified CCS radical it became possible to study the magnetic field associated with dense ($\sim 10^5\ cm^{-3}$) dark cloud cores, the potential sites of future star formation. We report the detection of a $-110\,\mu$G field towards TMC-1C, a low-mass core associated with the Taurus Molecular Cloud. From complementary gas density and kinetic temperature probing measurements, we derive approximate equipartition between magnetic, gravitational and thermal energy for this clump.

1. Introduction

The best and direct observational access to the magnetic field strength in the neutral interstellar medium is via the Zeeman effect. During the last few years, improved sensitivity and observing techniques have made it possible to derive weak Zeeman splittings in the HI λ 21 cm and OH λ 18 cm transitions for a couple of interstellar clouds (Heiles, 1987, and T.Troland's review at this meeting). Field strengths reported so far range from a few μG in the diffuse interstellar medium (gas densities $\lesssim$ 100 cm^{-3}) and a few 10 μG in dark cloud envelopes ($n \sim 10^3\ cm^{-3}$), to a few mG in OH masing layers ($n \sim 10^{7-8}\ cm^{-3}$). Here we report results of recent Zeeman activities with the MPIfR 100-m telescope towards ultra-dense ($\sim 10^{10}\ cm^{-3}$) compact interstellar water maser spots and dense cores ($\sim 10^5\ cm^{-3}$) in the nearby Taurus dark cloud complex.

In the presence of a weak magnetic field a molecular transition (J–J',F–F') splits into two groups of slightly frequency-shifted, oppositely circularly polarized line components. The amplitude $T_B(V)$ of the difference spectrum between the right- and left-handed circularly polarized emission, equivalent to the Stokes parameter 'V', scales directly with the magnetic field component parallel to the line-of-sight, $B_{||}$

$$\frac{T_B(V)}{T_B(I)} = \mathcal{A}_{J-J'} \cdot \frac{B_{||}[\mu G]}{\Delta v[km\,s^{-1}]}.$$

Δv is the observed linewidth, and the Zeeman splitting factor $\mathcal{A}_{J-J'}$ describes the coupling

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Table 1: Comparison of Zeeman Characteristics

species	frequency [GHz]	$\mathcal{A}_{J-J'}$ [km s^{-1}G^{-1}]	density [cm^{-3}]	linewidth [km s^{-1}]
HI	1.42	422.	$\lesssim 100$	
$OH(^2\Pi_{3/2};J=3/2)$	1.66	420.	$\sim 10^3$	$\gtrsim 1$
$CCS(1_0\text{-}0_1)$	11.12	16.	10^{4-5}	~ 0.2
$H_2O(6_{16}\text{-}5_{23})$	22.23	0.01	10^{10}	$\gtrsim 0.5$

of the transition to the external field. Table I presents a compilation of Zeeman characteristics for relevant lines, including estimates of typical linewidths and gas densities in the emission/absorption layers.

2. Strong magnetic fields in interstellar H_2O masers

We briefly summarize results from our winter 1988 circular polarization experiment in the $H_2O(6_{16}\text{-}5_{23})$ maser transition at 22.235 GHz – for a more detailed discussion we refer to Fiebig and Güsten (1989), and for confirming measurements, see Moran et al. (at this meeting). Weak difference spectra towards several galactic maser features were detected. For the non-paramagnetic H_2O molecule, the Zeeman splitting is due to interaction of the field with the nuclear magnetic moment only, and the observed frequency shift is about 3 orders of magnitude below the thermal linewidth of these lines. Inferred splittings of a few 10 kHz imply magnetic field strengths of ~ 50 mG in the high-density H_2O masing layers ($n \sim 10^{10\pm1}$ cm^{-3}), representing by far the strongest fields ever ***directly*** observed in the interstellar medium. Fig. 1 shows results for the prominent W49N maser cluster, for which due to its wide velocity coverage and high luminosity, V-spectra of in total 9 individual velocity features could be analyzed. Approximate equipartition between magnetic, thermal and mechanical energy implies that during the short-lived maser phenomenon ($\tau \sim 10^{7-8}$ s), the field remains frozen to the (shock-compressed) dense gas clump giving rise to H_2O maser amplification. With the comparatively low field strengths inferred now, current maser pump scenarios (e. g., Kylafis and Norman, 1987) have to be reconsidered.

3. A CCS Zeeman study towards dark cloud cores

Studying the physical characteristics of dense cloud cores, the potential sites of future low-mass star formation, and in particular, evaluating the importance of the magnetic field for their dynamical evolution, are of great importance for our theoretical understanding of the late star formation process. The recently identified CCS radical (Saito et al., 1987) made possible now to investigate, with high spatial resolution, the magnetic field strength in the dense cores of nearby dark cloud complexes, thus complementing lower gas density sampling OH-data.

We performed deep 'Zeeman'-integrations in the $CCS(1_0\text{-}0_1)$ ground-state transition (at $\nu = 11.12$ GHz) towards 4 compact cores (typical size: 0.05 - 0.10 pc) in the nearby Taurus molecular cloud (distance ~140 pc). Towards the southern core of TMC-1C (Fig. 2) a weak V-spectrum was detected, $T_B(V) \sim 1.5\,10^{-2}$ K, while otherwise only upper limits were

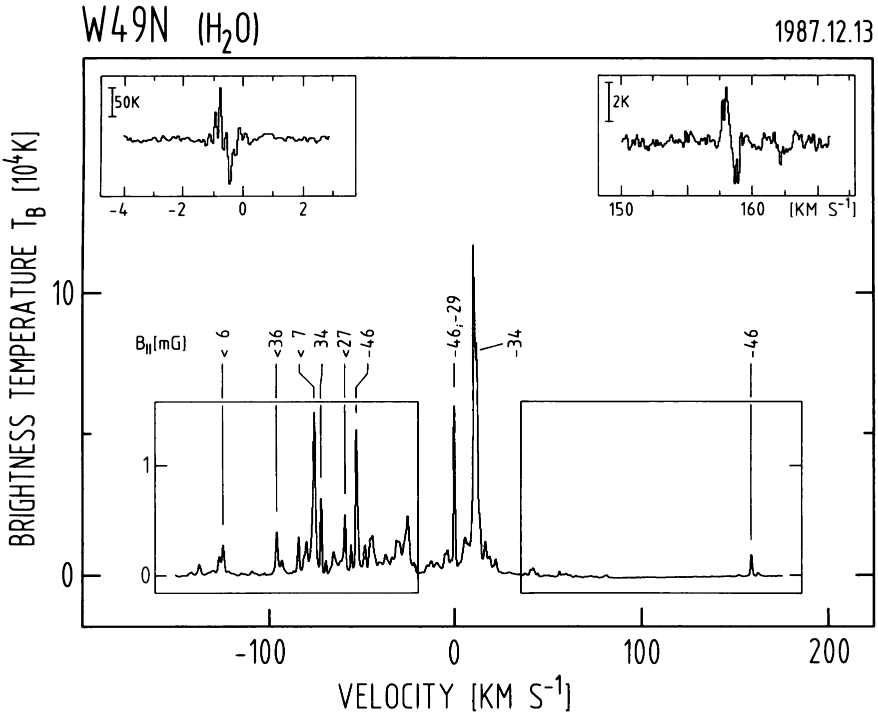

Figure 1: Composite total power spectrum of the W49N H_2O maser source. The magnetic field strength $B_{||}$ inferred for individual spots is given. For two of the masers (at v_{lsr}= −0.6 km s^{-1} and +158.3 km s^{-1}) difference spectra between the right- and left-handed circularly polarized emission are inserted.

obtained. As no laboratory determination of the $g_{J=1}$ factor is available so far, we solved the wave equation for the $J_N = 1_0$ level as linear combination of *Hund's case(a)* basic states (for the low-J levels this seems the more likely coupling scheme), and calculate $g_{J=1} = 0.3$ ($\mathcal{A}_{1-0} \sim 16$). This yields, with an estimated uncertainty of factor 2, a magnetic field strength towards TMC-1C of $B_{||}$ = -110 μG, and upper limits towards the other cores as small as $\sim$40 μG (TMC-1SE).

With a gas density of $\sim 10^{5\pm.5}$ cm^{-3} (as consistently derived from excitation studies of complementary NH_3 and C_3H_2 data, but also by applying the virial theorem) and a uniform kinetic temperature of 9-10 K (from the lower NH_3 metastable transitions) approximate equipartition between magnetic, gravitational and thermal energy is calculated for the TMC-1C core (mass: $\sim$5 $M_\odot$). No complementary OH-data, sampling the lower-density envelope gas, are yet available for this particular clump, but if Goodman et al.'s detection of a $\sim$27 μG field towards the B1 cloud envelope ($n \sim 10^3$ cm^{-3}) is taken representative also for TMC-1C, one infers $B \propto n^{0.3}$, in close agreement with theoretical predictions for self-gravitating clouds (Mouschovias, Mestel at this meeting). Hence for TMC-1C, the

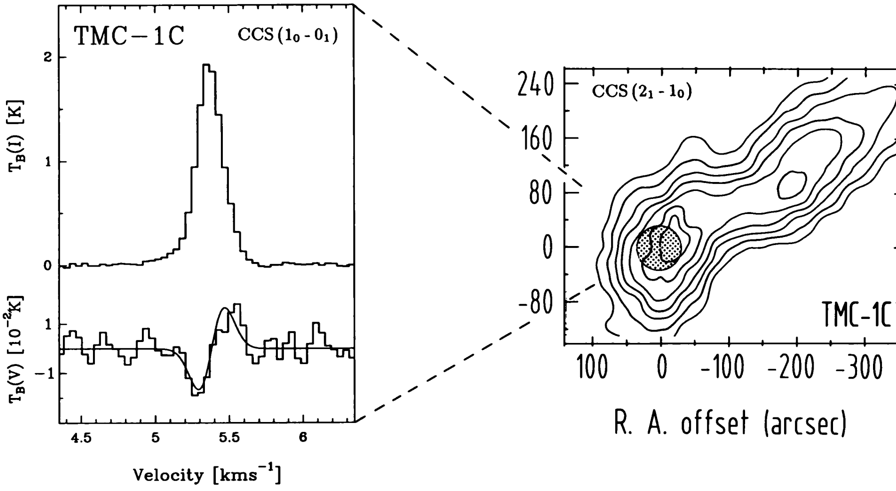

Figure 2: Velocity-integrated CCS(2_1-1_0) emission of the TMC-1C cloud core in the nearby Taurus molecular cloud (at a distance of ~140 pc, 1' ≡ 0.04 pc). Offsets refer to $(\alpha,\delta)_{50}$ = (04 38 31.5; 25 55 00). Towards the southern core, a weak V-spectrum ('L'–'R') was detected in the (1_0-0_1) ground-state transition, corresponding to a magnetic field strength $B_{||} \simeq -110\,\mu$G. A theoretical Zeeman pattern has been superimposed on the spectrum.

magnetic field appears still dynamically coupled to the gas, and may counterbalance self-gravity. Notably however, the non-thermal velocity dispersion in all the Taurus cores is far below the thermal line broadening, and if related to the Alfvén velocity suggests a '*turbulent*' field component of 20μG at most.

Obviously, to further constrain the physical state of these cores, both a better understanding of the CCS molecular constants (best by a laboratory determination of the g_J-factor), and complementary OH measurements of the surrounding lower density medium need to be obtained.

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