Astron. Astrophys. 224, 206–208 (1989)

ASTRONOMY
AND
ASTROPHYSICS

Zeeman splitting in interstellar molecules

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Received January 18, accepted April 17, 1989

Summary. We have calculated the Zeeman splitting due to a longitudinal magnetic field on some transitions of diatomic molecules (others than OH) which are currently observed in the interstellar clouds. Only CN and SO exhibit effects comparable to that of OH. Their observability in the millimeter range is discussed and real possibilities are open as soon as the magnetic field is of the order of 100 μG. In the same wavelength range, O_2 would exhibit Zeeman effects even larger than that of OH but must be observed from space radiotelescopes.

Key words: interstellar medium: clouds – magnetic field molecules – radio lines: molecular

1. Introduction

The magnetic field has become recognised as an unavoidable ingredient to be taken into account in the study of interstellar clouds. Clouds must be supported against their own gravitational field, unless the star formation rate would be very much larger than observed. Thermal pressure gradients in dense interstellar cores (where the temperature $T \approx 10$–20 K) are unable to provide this support at least on large scales and probably the same is true of centrifugal forces. One possibility is that turbulent pressure provides the primary support against gravity but such a turbulence which has to be supersonic raises difficult questions concerning the necessary exitation mechanism. Another possibility is to support molecular clouds by the effective pressure of an internal magnetic field. Some observations tend to support this view, but it is not clear at what stage of the evolution the magnetic field becomes large enough to support the cloud and when it becomes dynamically important.

On the other hand, the challenging question of star formation is that a large fraction of the magnetic flux (Mestel, 1983; Paleologou et al., 1983) must be lost during the collapse. Measurements of the longitudinal magnetic field in molecular clouds are obtained only by Zeeman splitting of the 18 cm OH line (and in more diffuse clouds by the 21 cm H I line). As far as the hydrogen number density is known, the general tendency is an increase of the magnitude of this longitudinal magnetic field with increasing molecular number density (up to $\approx 10^5\,\mathrm{cm}^{-3}$). This raises interesting questions concerning the phase of the cloud evolution at which this increase must obviously stop. It would be useful to do further observations with OH and with one or more molecule (or radical) with particular emphasis on molecules which could be the tracers of high densities.

The aim of this paper is to estimate the Zeeman effect for diatomic molecular currently observed in molecular clouds and to check the possibility of their detection.

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2. Calculated Zeeman splittings for some observed diatomic molecules

We have done detailed calculations of the Zeeman effect in the dozen diatomic molecules identified in the interstellar clouds.

The results, presented in Table 1, have been obtained by following standard procedure of quantum mechanics and using molecular data from Gordy and Cook (1984) and papers indicated therein. In particular, for CN (electronic $^2\Sigma$ ground-state) the Zeeman splitting has been calculated from the molecular g-factor as appropriately given in Sect. 11.8.b of Gordy and Cook's book and by taking into account the hyperfine structure as explained in Sect. 11.2.a of that same reference. As to SO (electronic $^3\Sigma$ ground-state), it is better represented by a case intermediate between Hund's cases (a) and (b) and, therefore, we have adopted the g-factor given by Clark and Johnson (1974).

It turns out that only CN and SO exhibit an effect comparable to that in OH. The magnitude of this effect is best appreciated in terms of the frequency separation, $2\Delta\nu$(Hz), of the σ-components for a given magnetic field strength, B (μG). (The π-components are not detected with the current instrumental arrangements). We give the magnitude of this separation for selected transitions in CN and SO (OH is given for comparison). The selected transitions correspond to those observed in the interstellar medium. As it is virtually hopeless with the current telescopes to resolve the σ-components of a multiplet, the value given in Table 1 accordingly corresponds to the separation averaged over σ-components of a given polarisation weighed by their relative intensities at thermodynamical equilibrium.

The other observed diatomic molecules do not appear in Table 1: CO, CS, SiO and SiS exhibit separations of the order of a few $10^{-4}\,\mathrm{Hz}\,\mu\mathrm{G}^{-1}$ and the corresponding values for the NO, NS and CH are still smaller. (We did not calculate the values for C_2 and PN.)

Table 1. Separation of the Zeeman σ-components for selected transitions in CN and SO; OH is recalled for comparison

Molecule	Transition	Frequency (MHz)	FWHM ($km\,s^{-1}$)	Zeeman splitting $2\Delta\nu/B$ (Hz/μG)
$^{12}C^{14}N$	$N, J, F \rightarrow N', J', F'$			
	1, 3/2, 3/2→0, 1/2, 1/2	113488.1	$5.7\ 10^{-6}$	2.2
	1, 3/2, 5/2→0, 1/2, 3/2	113490.9	$1.6\ 10^{-6}$	0.6
	2, 3/2, 3/2→1, 3/2, 5/2	226332.5	$3.3\ 10^{-6}$	2.6
	2, 3/2, 5/2→1, 3/2, 5/2	226359.5	$8.6\ 10^{-6}$	0.2
	2, 5/2, 5/2→1, 3/2, 3/2	226874.2	$0.9\ 10^{-6}$	0.7
	2, 5/2, 7/2→1, 3/2, 5/2	226874.8	$0.5\ 10^{-6}$	0.4
	2, 5/2, 3/2→1, 3/2, 1/2	226874.9	$1.6\ 10^{-6}$	1.2
$^{32}S^{16}O$	$N, J \rightarrow N', J'$			
	0, 1→1, 0	30001.5	$\leqq 1.0\ 10^{-8}$	$\leqq 10^{-3}$
	2, 3→1, 2	99299.9	$3\ 10^{-6}$	1.0
	3, 4→2, 3	138178.6	$1.7\ 10^{-6}$	0.8
	4, 3→3, 2	158971.8		1.0
	5, 5→4, 4	215220.6	$\leqq 1.4\ 10^{-9}$	$\leqq 10^{-3}$
	5, 6→4, 5	219949.9	$6.8\ 10^{-7}$	0.5
	2, 1→1, 2	236452.3	$2\ 10^{-6}$	1.7
$^{16}O^{1}H$	$J, F \rightarrow J', F'$			
	3/2, 1→3/2, 1	1665.4	$5.9\ 10^{-4}$	3.27
	3/2, 2→3/2, 2	1667.3	$3.5\ 10^{-4}$	1.96

Table 2. Observational data on the CN molecule without polarisation measurements

Transition $N, J, F \rightarrow N', J', F'$	Source	T_A^* (K)	Δv ($km\,s^{-1}$)	Ref.
1, 3/2, 3/2→0, 1/2, 1/2	TMC-1	0.53	0.5	1
	TMC-1	0.39	0.77	2
	L1535	0.69	0.4	1
	L134	0.29	0.41	2
	ϱ Oph	0.50	1.37	2
1, 3/2, 5/2→0, 1/2, 3/2	TMC-1	0.35	0.91	2
	L134	0.38	0.51	2
	ϱ Oph	0.81	1.33	2
2, 5/2, 5/2→1, 3/2, 3/2 2, 5/2, 7/2→1, 3/2, 5/2 2, 5/2, 3/2→1, 3/2, 1/2	Orion	9.1	5.6[a]	3
2, 5/2, 3/2→1, 3/2, 1/2	OMC-1	8.0[b]	4.0	4
	OMC-1	3.8[b]	3.0	4
	OMC-2	3.8[b]	4.0	4
	Orion A	1.42	4.8	5
	Orion A	4.08	3.7	5

[a] Δv is obtained as the ratio of $\int T_A^*\, dv$ along the line and T_A^*.
[b] The temperature is the brightness temperature as given by the observers; the three transitions are unresolved.

References: (1) Churchwell and Bieging (1984); (2) Crutcher et al. (1984); (3) Sutton et al. (1982); (4) Wootten et al. (1982); (5) Turner and Thaddeus (1977).

Table 3. Observational data on the SO molecule without polarisation measurements

Transition $N, J \rightarrow N', J'$	Source	T_A^* (K)	Δv ($km\,s^{-1}$)	Ref.
0, 1→1, 0	L134	1.95	2.30	1
	Orion A	≦ 0.4		2
	SgB_2	0.4	19.0	2
2, 3→1, 2	Orion A	1.01	8.3	2
	Orion A	1.59	8.7	2
	ϱ Oph	1.37	1.5	2
1, 2→1, 1	OMC 1	1.1	4.8	3
	OMC 1	0.61	10.6	3
4, 3→3, 2	NGC 2024	2.15	2.5	2
	NGC 2264	2.05	2.2	2
5, 5→4, 4	Orion A	20.2	28.1[a]	4
5, 6→4, 5	Orion A	24.7	27.5[a]	4

[a] Δv is obtained as the ratio of $\int T_A^*\, dv$ along the line and T_A^*.

References: (1) Rydbeck et al. (1980); (2) Gottlieb et al. (1978); (3) Clark et al. (1979); (4) Sutton et al. (1982).

3. Is the magnetic field amenable to measurements?

In order to prospect the possible detection of the Zeeman splittings on CN and SO, we recall in Tables 2 and 3 some observational data in the centimeter and millimeter ranges.

Let us estimate the magnetic field strength that could be measured with the European radiotelescope in the millimeter wavelength range, viz. the 30 m IRAM telescope.

We can see from Table 1 that the magnitude of the Zeeman splitting, whenever noticeable, is $2\Delta\nu \approx 1\,\mathrm{Hz}\,\mu\mathrm{G}^{-1}$. Most transitions have their frequency ≈ 100–200 GHz. Besides, the FWHM of the transitions in the Tables 2 and 3 is ≈ 1–$10\,\mathrm{km\,s^{-1}}$, i.e. $\Delta\nu_1 \approx 0.3$–6 MHz and the antenna temperature T_A^* is ≈ 1 K. For a Zeeman splitting of $2\Delta\nu$, the antenna output (obtained by substracting the two opposite circularly polarised signals) is for a given magnetic field B:

$$\Delta T \approx (2\Delta\nu)\, BT_A^*/\Delta\nu_1 .$$

To be detectable, this signal should of course be greater than the minimum detectable temperature ΔT_{rms} of the telescope which corresponds to a given pre-detection bandwidth Δf and observation time τ. This yields the minimum detectable magnetic field

$$B_{\mathrm{rms}} \approx \Delta T_{\mathrm{rms}}\, \Delta\nu_1/(2\Delta\nu)\, T_A^* .$$

For the IRAM telescope:

$$\Delta T_{\mathrm{rms}} \approx T_{\mathrm{sys}}/(\Delta f\,\tau)^{1/2}$$

where $T_{\mathrm{sys}} = 600$ or 1000 K according to whether the 230 or 115 GHz-receptor is used.

For a typical pre-detection bandwith of 1 MHz and a time $\tau \approx 50$ h (which is of the order of the observation time for OH observations),

$$\Delta T_{\mathrm{rms}} = 3\text{–}5\,\mathrm{mK}$$

i.e. B_{rms} is of the order of a few 100 μG.

This value is not desperately high; indeed, it is of the order of magnitude one could expect in moderately dense clouds with a number density of molecular hydrogen of the order of 10^4–$10^5\,\mathrm{cm}^{-3}$. It is also of the order of magnitude of what has been measured in interstellar clouds with OH (Kazès and Crutcher, 1986). In view of the better resolution of the IRAM telescope (i.e. 8″ at 230 GHz for IRAM versus 20′ at 1665 MHz for Nançay), one may hope to access to some spatial structure of the magnetic field inside an individual cloud.

Of course, magnetic field well in excess of B_{rms} are more easily observable. Magnetic strengths larger than a few mG have been inferred theoretically (Heyvaerts et al., 1988; Benford, 1988) or observationally (Yusef-Zadeh et al., 1987) near the galactic center. Observing the above mentionned molecules in the millimeter range should enable one to test these hypotheses.

Besides, a diatomic molecule which is hardly observable from groundbased telescopes is predicted from steady state models (i.e. Viala and Walmsley, 1976; Clavel et al., 1978; Boland and De Jong, 1984; Viala, 1986) to have an abundance comparable to that of CO, deep inside molecular clouds; this molecule is O_2. It turns out that the rotational transitions of this molecule exhibit a pronounced Zeeman effect, even stronger than that of OH (Hill and Gordy, 1954); the splitting of the $N = 1$ level is given in Table 4. Unfortunately, these transitions are strongly absorbed in the atmosphere. The way out of this inconvenience would be to use a space-borne telescope in the millimeter range such as the ESA project FIRST. Preliminary calculations based on the predicted abundances reveal that observing this molecule could be a feasable means of determining the magnetic field inside the cores of interstellar clouds.

Table 4. Separation of the Zeeman σ-components for the $N = 1$ level in O_2 from Hill and Gordy (1954)

Molecule	Transition	Frequency (MHz)	Zeeman splitting $2\Delta\nu/B$ (Hz/μG)
$^{16}O_2$	$N, J \rightarrow N', J'$		
	$1, 1 \rightarrow 1, 2$	118750.7	2.80
	$1, 1 \rightarrow 1, 0$	56264.7	2.80

Acknowledgements. We want to thank J. Vigué and G. Gouedard, F. Combes, J. Crovisier, S. Leach, and Y.-P. Viala for valuable information.

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