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Zeeman splitting in interstellar molecules

II. The ethynyl radical

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Abstract. The Zeeman splitting that a longitudinal magnetic field would produce on the ethynyl radical is calculated for the transitions typical of those observed in the interstellar clouds. It turns out that the ubiquitous CCH radical adds to the list of the few interstellar molecules that could be used to determine magnetic fields in molecular clouds.

Key words: ISM: clouds – ISM: magnetic fields – ISM: molecules – radio lines: ISM

1. Introduction

It has become increasingly clear that magnetic fields must play an important role in supporting molecular clouds against self-gravity, and thereby in the process of star formation. Although the question of the cloud support via magnetic fields is far from being settled, the invocation of magnetic fields seems to be a promising alternative to the deficiencies of the non-magnetic mechanisms that have been proposed so far (see, for example, McKee et al. 1993 for a good review). An essential parameter in this context is the mass-to-flux ratio, M/Φ_B. If it exceeds a certain critical value, the magnetic field is unable to prevent the cloud from gravitational collapse; on the contrary, if it is less than this value, gravitational collapse is impossible, so long as magnetic flux freezing holds (for a detailed discussion of the issues and for full numerical models, see, for example, Mouschovias 1991; Basu & Mouschovias 1995; and the references cited in these papers). The measurement of magnetic fields in molecular clouds is therefore of paramount importance. This led, more than a decade ago, several astronomers to start carrying out an extensive observation program aimed to detect the Zeeman effect in spectral lines arising in the clouds (Crutcher et al. 1994, 1996; Heiles et al. 1993; Troland et al. 1982, 1996). Until recently, these observations were made exclusively in the lines of H I and OH. But, noting that in general $[\mathrm{OH}/\mathrm{H_2}]$ decreases when the cloud density increases (Troland et al. 1996) Crutcher et al. (1996) made a first attempt to detect magnetic fields in molecular cloud cores through the Zeeman effect in the CN lines, without much success however.

Having in mind, like these observers, that the use of just one species (OH, for example) cannot be sufficient to measure magnetic fields in every part of a given molecular cloud, we had started, several years ago, a systematic investigation of the Zeeman splitting in interstellar molecules (Bel & Leroy 1989; hereafter Paper I). In Paper I, we considered virtually all diatomic molecules observed in the interstellar medium; the net result was that only CN, SO and O_2 exhibit Zeeman effects comparable to that of OH. In view of the diversity and complexity of the polyatomic molecules, and also of their comparatively lower abundance, we decided to restrict our study to those that are found in many places and whose structure allows the Zeeman splitting to be calculated with reasonable realiability. As a result, we were left essentially with linear tri-atomic molecules, of which we only retained CCH, the ethynyl radical, whose ubiquity is well established (Tucker et al. 1974; Baudry et al. 1980; Wooten et al. 1980; van Dishoeck et al. 1995). [We excluded CCS essentially because of the difficulty to treat its ground state properly. Technically, CCS is a linear radical with a $^3\Sigma$ ground state which qualifies for a coupling of the angular momenta intermediate between Hund's cases a and b, and exhibits complex selection rules (Fuente et al. 1990; Suzuki et al. 1992), which lessens somewhat the reliability of corresponding Zeeman splitting calculations.]

2. The Zeeman splitting in CCH

Experimental studies have established beyond doubt that CCH is a linear molecule and has a $^2\Sigma$ ground state (Graham et al. 1974; Sastry et al. 1981; Gottlieb et al. 1983). From both laboratory and astrophysical data it has been established that the angular momentum coupling scheme of CCH follows Hund's case $b_{\beta J}$ (Townes & Schawlow 1975) to a reasonable approximation (Sastry et al. 1981; Ziurys et al. 1982; Gottlieb et al. 1983). Accordingly, we have

$$\boldsymbol{J} = \boldsymbol{N} + \boldsymbol{S} \quad \text{and} \quad \boldsymbol{F} = \boldsymbol{J} + \boldsymbol{I},$$

where $\boldsymbol{N}$ is the rotational angular momentum, $\boldsymbol{S}$ the electron spin, $\boldsymbol{J}$ the angular momentum and $\boldsymbol{I}$ the spin of the hydrogen

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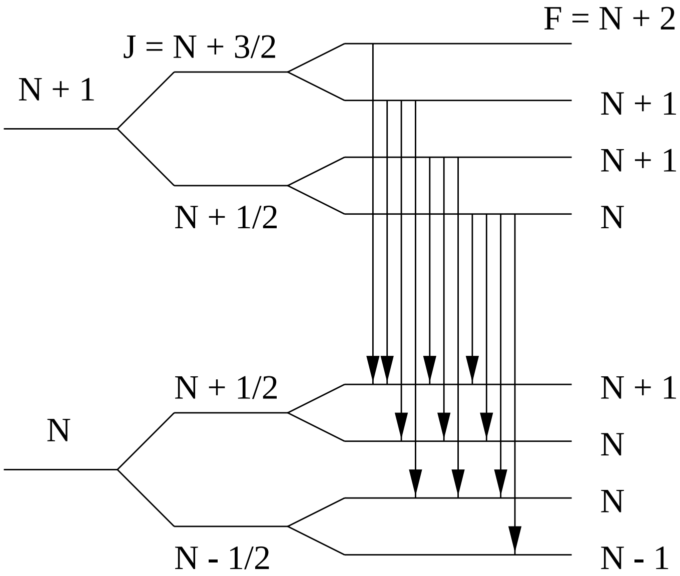

Fig. 1. The $N+1 \rightarrow N$ energy level diagram of CCH showing all allowed transitions. (Mixing of the J energy levels causes the usual selection rule $\Delta J = 0, \pm 1$ to break down, hence the transition $|N+1, N+3/2, N+1\rangle \rightarrow |N, N-1/2, N\rangle$.) When $N = 0$, the lower rotational level has only one fine structure J level, viz. $J = N + 1/2$.

nucleus. Yet, as indicated by Ziurys et al. (1982), due to the mixing of J-states by the hyperfine interaction, J is no longer a good quantum number, and the usual selection rules $\Delta J = 0, \pm 1$ no longer hold. Rather, the selection rules for electric dipole transitions now are

$$\Delta F = 0, \pm 1 \quad \text{(with } F = 0 \rightarrow 0 \text{ forbidden)}.$$

Fig. 1 shows the allowed transitions between rotational levels $N+1$ and N, with fine and hyperfine splittings included.

The magnetic fields prevailing in the interstellar medium are so weak that they do not decouple the angular momentum $\boldsymbol{J}$ and the nuclear spin $\boldsymbol{I}$. Their effect is just to lift the degeneracy of the hyperfine levels F by splitting them into $2F+1$ levels, labeled by the quantum number M_F ($M_F = F, F-1, F-2, \ldots, -F$). The Zeeman interaction energy is usually written as

$$E_B(M_F) = -g_F \mu_B B M_F,$$

where μ_B is the Bohr magneton, B the magnetic field, and g_F a dimensionless coefficient known as the Landé factor. The frequency of the emitted radiation for a transition between Zeeman sublevels $|N+1, J', F', M_{F'}\rangle$ and $|N, J, F, M_F\rangle$ is given by

$$\nu = \nu_0 + \left[(g_F - g_{F'})M_F - g_{F'}\Delta M_F\right](\mu_B B/h),$$

where ν_0 is the frequency of the transition without magnetic field, $\Delta M_F = M_{F'} - M_F$, and the index F corresponds to the lower level.

The selection rules for transitions between the sublevels of the rotational levels $N+1$ and N are

$$\Delta M_F = 0, \pm 1.$$

Table 1. Separation, $2\Delta\nu/B$, of the Zeeman σ-components for the $N = 1 \rightarrow 0$ transition of CCH

Transition N, J, F	 $\rightarrow$	 N', J', F'	Frequency[a] (MHz)	$2\Delta\nu/B$ (Hz μG^{-1})
$N = 1 \rightarrow 0$				
1, 3/2, 1	$\rightarrow$	0, 1/2, 1	87,284.42	2.6
1, 3/2, 2	$\rightarrow$	0, 1/2, 1	87,317.23	0.70
1, 3/2, 1	$\rightarrow$	0, 1/2, 0	87,328.92	2.3
1, 1/2, 1	$\rightarrow$	0, 1/2, 1	87,402.34	0.93
1, 1/2, 0	$\rightarrow$	0, 1/2, 1	87,407.46	2.8
1, 1/2, 1	$\rightarrow$	0, 1/2, 0	87,446.84	0.93

[a] The line frequencies are from Ziurys et al. (1982).

From the expressions given by Gordy & Cook (1970) it is easily established that, for the values of the rotational levels we are considering in this paper ($0 \leq N \leq 5$), the Landé factor can be written as

$$\begin{aligned} g_F \approx\ & [J(J+1) - N(N+1) + S(S+1)] \times \\ & \times [F(F+1) + J(J+1) - I(I+1)]/J(J+1). \end{aligned}$$

Under interstellar conditions, $\Delta\nu = |\nu - \nu_0|$ is much less than the full line width at half-maximum (FWHM), so that the individual transitions cannot be resolved, making the Zeeman effect very difficult to detect. However, among all these transitions, the so-called σ transitions (corresponding to $\Delta M_F = \pm 1$) are elliptically polarized, with the circularly polarized portion due to the line-of-sight component of the magnetic field. By substracting the left from the right circular polarization of the radio signal, the amplitude of the obtained Stokes V spectrum is proportional to the strength of the line-of-sight component of the magnetic field and to the average frequency separation between the oppositely polarized σ components (Verschuur 1969; Troland & Heiles 1982). The average is obtained by weighing the frequency separation of the individual pairs of σ transitions by their relative intensity. The relevant expressions for the latter are (Gordy & Cook 1970)

$$\begin{aligned} I(M_F) &= P(F \pm M_F + 1)(F \pm M_F + 2) \quad (\Delta M_F = 1) \\ I(M_F) &= Q(F \mp M_F)(F \pm M_F + 1) \quad (\Delta M_F = 0) \\ I(M_F) &= P(F \mp M_F)(F \mp M_F + 1) \quad (\Delta M_F = -1) \end{aligned}$$

where F is the smaller of the two F's involved in the transition and the upper sign is taken throughout for the $M_F \rightarrow M_F + 1$ transition and the lower sign for the $M_F \rightarrow M_F - 1$ transition. The coefficients P and Q are independent of M_F.

Tables 1 to 5 give the resulting average frequency separation of the left and right circularly polarized portions of the σ transitions for the transitions listed in Ziurys et al. (1982).

3. Conclusions

In order to prospect the possible detection of the Zeeman splittings in the CCH radical, we shall estimate the minimum line-of-sight magnetic field that could be observed with typical facilities such as, e.g., the $12\,\mathrm{m}$ telescope of the National Radio

Table 2. Separation, $2\Delta\nu/B$, of the Zeeman σ-components for the $N = 2 \rightarrow 1$ transition of CCH

Transition N, J, F	$\rightarrow$	N', J', F'	Frequency[a] (MHz)	$2\Delta\nu/B$ (Hz $\mu\mathrm{G}^{-1}$)
$N = 2 \rightarrow 1$				
2, 5/2, 2	$\rightarrow$	1, 1/2, 1	174,550.20	2.4
2, 5/2, 2	$\rightarrow$	1, 3/2, 2	174,635.32	1.4
2, 5/2, 3	$\rightarrow$	1, 3/2, 2	174,663.68	0.47
2, 5/2, 2	$\rightarrow$	1, 3/2, 1	174,668.12	0.79
2, 3/2, 2	$\rightarrow$	1, 1/2, 1	174,722.22	0.79
2, 3/2, 1	$\rightarrow$	1, 1/2, 0	174,728.53	1.4
2, 3/2, 1	$\rightarrow$	1, 1/2, 1	174,733.65	1.2
2, 3/2, 2	$\rightarrow$	1, 3/2, 2	174,807.33	0.28
2, 3/2, 1	$\rightarrow$	1, 3/2, 2	174,818.77	2.8
2, 3/2, 2	$\rightarrow$	1, 3/2, 1	174,840.14	2.4
2, 3/2, 1	$\rightarrow$	1, 3/2, 1	174,851.57	0.47

[a] The line frequencies are from Ziurys et al. (1982).

Table 3. Separation, $2\Delta\nu/B$, of the Zeeman σ-components for the $N = 3 \rightarrow 2$ transition of CCH

Transition N, J, F	$\rightarrow$	N', J', F'	Frequency[a] (MHz)	$2\Delta\nu/B$ (Hz $\mu\mathrm{G}^{-1}$)
$N = 3 \rightarrow 2$				
3, 7/2, 3	$\rightarrow$	2, 3/2, 2	261,834.69	2.6
3, 7/2, 3	$\rightarrow$	2, 5/2, 3	261,978.34	0.92
3, 7/2, 4	$\rightarrow$	2, 5/2, 3	262,004.52	0.35
3, 7/2, 3	$\rightarrow$	2, 5/2, 2	262,006.70	0.49
3, 5/2, 3	$\rightarrow$	2, 3/2, 2	262,065.16	0.49
3, 5/2, 2	$\rightarrow$	2, 3/2, 1	262,067.65	0.70
3, 5/2, 2	$\rightarrow$	2, 3/2, 2	262,079.09	0.89
3, 5/2, 3	$\rightarrow$	2, 5/2, 3	262,208.81	0.13
3, 5/2, 2	$\rightarrow$	2, 5/2, 3	262,222.74	2.8
3, 5/2, 3	$\rightarrow$	2, 5/2, 2	262,237.18	2.6
3, 5/2, 2	$\rightarrow$	2, 5/2, 2	262,251.10	0.19

[a] The line frequencies are from Ziurys et al. (1982).

Astronomy Observatory or the $14\,\mathrm{m}$ telescope of the Five College Astronomy Department Observatory.

For a Zeeman splitting of $2\Delta\nu$, the antenna output obtained by substracting the two opposite circularly polarized signals is given by

$$\Delta T \approx (2\Delta\nu) B_{\mathrm{los}} T_A^{\star} / \Delta\nu_1,$$

where B_{los} is the line-of-sight component of the magnetic field, $T_A^{\star}$ the antenna temperature and $\Delta\nu_1$ the FWHM of the transition observed. The minimum temperature ΔT_{rms} that is detectable by observing over a period of time t with a pre-dectection bandwith Δf is

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

so that the minimum detectable line-of-sight magnetic field is

$$B_{\mathrm{los}} \approx (1/2\Delta\nu)(T_{sys}/T_A^{\star})\Delta\nu_1/(\Delta f t)^{1/2}.$$

Table 4. Separation, $2\Delta\nu/B$, of the Zeeman σ-components for the $N = 4 \rightarrow 3$ transition of CCH

Transition N, J, F	$\rightarrow$	N', J', F'	Frequency[a] (MHz)	$2\Delta\nu/B$ (Hz $\mu\mathrm{G}^{-1}$)
$N = 4 \rightarrow 3$				
4, 9/2, 4	$\rightarrow$	3, 5/2, 3	349,107.94	2.7
4, 9/2, 4	$\rightarrow$	3, 7/2, 4	349,312.22	0.69
4, 9/2, 5	$\rightarrow$	3, 7/2, 4	349,337.14	0.28
4, 9/2, 4	$\rightarrow$	3, 7/2, 3	349,338.41	0.36
4, 7/2, 4	$\rightarrow$	3, 5/2, 3	349,398.61	0.36
4, 7/2, 3	$\rightarrow$	3, 5/2, 2	349,399.99	0.47
4, 7/2, 3	$\rightarrow$	3, 5/2, 3	349,413.92	0.68
4, 7/2, 4	$\rightarrow$	3, 7/2, 4	349,602.89	0.078
4, 7/2, 3	$\rightarrow$	3, 7/2, 4	349,618.21	2.8
4, 7/2, 4	$\rightarrow$	3, 7/2, 3	349,629.08	2.7
4, 7/2, 3	$\rightarrow$	3, 7/2, 3	349,644.39	0.10

[a] The line frequencies are from Ziurys et al. (1982).

Table 5. Separation, $2\Delta\nu/B$, of the Zeeman σ-components for the $N = 5 \rightarrow 4$ transition of CCH

Transition N, J, F	$\rightarrow$	N', J', F'	Frequency[a] (MHz)	$2\Delta\nu/B$ (Hz $\mu\mathrm{G}^{-1}$)
$N = 5 \rightarrow 4$				
5, 11/2, 5	$\rightarrow$	4, 7/2, 4	436,368.98	2.7
5, 11/2, 5	$\rightarrow$	4, 9/2, 5	436,634.73	0.56
5, 11/2, 6	$\rightarrow$	4, 9/2, 5	436,658.82	0.23
5, 11/2, 5	$\rightarrow$	4, 9/2, 4	436,659.65	0.29
5, 9/2, 5	$\rightarrow$	4, 7/2, 4	436,720.69	0.29
5, 9/2, 4	$\rightarrow$	4, 7/2, 3	436,721.58	0.35
5, 9/2, 4	$\rightarrow$	4, 7/2, 4	436,736.89	0.55
5, 9/2, 5	$\rightarrow$	4, 9/2, 5	436,986.45	0.051
5, 9/2, 4	$\rightarrow$	4, 9/2, 5	437,002.65	2.8
5, 9/2, 5	$\rightarrow$	4, 9/2, 4	437,011.36	2.7
5, 9/2, 4	$\rightarrow$	4, 9/2, 4	437,027.56	0.062

[a] The line frequencies are from Ziurys et al. (1982).

As reported in the literature (Ziurys et al. 1982, Gottlieb et al. 1983, Ungerechts et al. 1997, Bergin et al. 1997), the observed rotational transitions typically have a FWHM of the order of a few MHz and yield an antenna temperature of a few Kelvins. With the progresses achieved in receiver technology, a typical system temperature at the frequencies under consideration is of the order of a few $100\,\mathrm{K}$. This leads to minimum detectable line-of-sight magnetic fields of the order of a few mG for a typical observing time $t \approx 30\,\mathrm{h}$. In view of these crude estimates, one can conclude that the rotational transitions of CCH exhibit a sensitivity sufficient for detecting magnetic fields of the order of magnitude one could expect from clouds with a molecular hydrogen density of the order of $10^5 - 10^6\,\mathrm{cm}^{-3}$, typical, e.g., of the regions traced by CCH in IRAS 16293-2422 (van Dishoeck et al. 1995).

Putting together these results and those of Paper I, we arrive at the conclusion that the only molecules for which a sufficient sensitivity can be reached to detect interstellar magnetic fields with the strengths expected in molecular clouds are: OH, CN, SO, O_2, CCH and, possibly, CCS (if one relies on rough estimates for the Zeeman splitting). The decrease in sensitivity of OH with density makes it necessary to use other molecules if one wants to probe magnetic fields in regions with typical densities $n(\mathrm{H}_2) \geq 10^4\,\mathrm{cm}^{-3}$ (Crutcher et al. 1996). Observational data on the dense giant molecular cloud cores in Orion, M 17 and Cepheus A (Bergin et al. 1997; Ungerechts et al. 1997), on the dark cloud TMC-1 (Irvine et al. 1991; Pratap et al. 1997) reveal that CN and CCH have very similar distributions and that CCH is more abundant than CN (by a factor of about $3-4$). Besides, if one notices that the $N=1\rightarrow 0$ transition of CCH is at a slightly lower frequency than the same transition in CN, and is therefore intrinsically marginally more sensitive to magnetic fields, one concludes that CCH should be worth as much consideration as CN as a molecule usable to detect magnetic fields in the dense cores of molecular clouds.

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References

Basu S., Mouschovias T. Ch., 1995, ApJ 453, 271
Baudry A., Combes F., Perault M., Dickman R., 1980, A&A 85, 244
Bel N., Leroy B., 1989, A&A 224, 206 (Paper I)
Bergin E. A., Ungerechts H., Goldsmith P. F., et al., 1997, ApJ 482, 267
Crutcher R. M., Mouschovias T. Ch., Troland T. H., Ciolek G. E., 1994, ApJ 427, 839
Crutcher R. M., Troland T. H., Lazareff B., Kazès I., 1996, ApJ 456, 217
Fuente A., Cernicharo J., Barcia A., Gómez-González J., 1990, A&A 231, 151
Gordy W., Cook R. L., 1970, Microwave Molecular Spectra, Interscience Publishers, J. Wiley & Sons (New Yord)
Gottlieb C. A., Gottlieb E. W., Thaddeus P., 1983, ApJ 264, 740
Graham W. R. M., Dismuke K. I., Weltner W. Jr., 1974, J. Chem. Phys. 60, 3817
Heiles C., Goodman A. A., McKee C. F., Zweibel E. G., 1993, Magnetic Fields in Star-forming Regions: Observations. In: Protostars and Planets III, Levy E. H. & Lunine J. I. (eds.), The University of Arizona Press (Tucson), 279
Irvine W. M., Ohishi M., Kaifu N., 1991, Icarus 91, 2
McKee C. F., Zweibel E. G., Goodman A. A., Heiles C., 1993, Magnetic Fields in Star-forming Regions: Observations. In: Protostars and Planets III, Levy E. H. & Lunine J. I. (eds.), The University of Arizona Press (Tucson), 327
Mouschovias T. Ch., 1991, Single-stage Fragmentation and a Modern Theory of Star Formation. In: The Physics of Star Formation and Early Stellar Evolution, Lada C. J. & Kylafis N. D. (eds), Kluwer (Dordrecht), 449
Pratap P., Dickens J. E., Snell R. L., et al., 1997, ApJ 486, 862
Sastry K. V. L. N., Helminger P., Charo A., Herbst E., De Lucia F. C., 1981, ApJ 251, L119
Suzuki H., Yamamoto S., Ohishi M., et al., 1992, ApJ 392, 551
Townes C. H., Schawlow A. L., 1975, Microwave Spectroscopy, Dover Publications (New York)
Troland T. H., Heiles C., 1982, ApJ 252, 179
Troland T. H., Crutcher R. M., Goodman A. A. et al., 1996, ApJ 471, 302
Tucker K. D., Kutner M. L., Thaddeus P., 1974, ApJ 193, L115
Ungerechts H., Bergin E. A., Goldsmith P. F., et al., 1997, ApJ 482, 245
van Dishoeck E. F., Blake G. A., Jansen D. J., Groesbeck T. D., 1995, ApJ 447, 760
Verschuur G. L., 1969, ApJ 156, 861
Wooten A., Bozyan E. P., Garett D. B., Loren R. B., Snell R. L., 1980, ApJ 239, 844
Ziurys L. M., Saykally R. J., Plambeck R. L., Erickson N. R., 1985, ApJ 254, 94