USING FIRST TO PROBE THE MAGNETIC FIELD WITH LOW-MASS MOLECULAR IONS.

Martin Houde[1], Thomas G. Phillips[2], Ruisheng Peng[1], Pierre Bastien[3] and Hiroshige Yoshida[1]

[1]Caltech Submillimeter Observatory, 111 Nowelo Street, Hilo, HI 96720
[2]California Institute of Technology, Pasadena, CA 91125
[3]Département de Physique, Université de Montréal, Montréal, Québec H3C 3J7, Canada

Abstract

Observations of the effects the magnetic field has on its environment are usually achieved using techniques which rely on its interaction with the spin of the particles under study. Because of the relative weakness of this effect, extraction of the field characteristics proves to be a most challenging task. We have recently presented a totally different approach to the problem and showed how and why a manifestation of the presence of the magnetic field can be directly detected in the spectra of ionic molecular lines. Our model makes predictions concerning the expected differences between the line profiles of coexistent ion and neutral molecular species and between ions of different mass. We have already published observational evidence in support of these predictions with spectra of neutral (HCN, $H^{13}CN$) and ion species of relatively high mass (HCO^+, N_2H^+, $H^{13}CO^+$, HCS^+) obtained in a sizeable sample of molecular clouds. Because of its frequency coverage, FIRST will allow us to study low-mass molecular species (H_2D^+, CH^+, H_3O^+) that are otherwise difficult or even impossible to observe with ground-based telescopes. It will then be possible to verify the applicability of our model to such molecular species and test the mass dependencies that it predicts.

1. Detection of the magnetic field.

It is possible to detect the presence of the magnetic field in the core of molecular clouds through a comparison of the line profiles of coexistent neutral and ion molecular species. To see how this can be done, we will consider a hypothetical region inhabited with a magnetic field where a given ion is subjected to a flow of neutral particles. We further assume that the plasma is weakly ionized, the neutral flow is linear and all collisions between the ion and the neutrals are perfectly elastic. Under these conditions, we find the following set of equations for the mean and variance of the ion velocity components in directions parallel and perpendicular to that of the mean magnetic field:

$$\left\langle \mathbf{v}_\parallel \right\rangle = \left\langle \mathbf{v}^n_\parallel \right\rangle \tag{1}$$

$$\langle \mathbf{v}_\perp \rangle = \frac{\langle \mathbf{v}^n_\perp \rangle + \langle \omega_r \rangle^{-1} \left[\langle \mathbf{v}^n_\perp \rangle \times \langle \overrightarrow{\omega_g} \rangle \right]}{1 + \left(\frac{\langle \overrightarrow{\omega_g} \rangle}{\langle \omega_r \rangle} \right)^2} \tag{2}$$

$$\sigma^2_\parallel = \frac{a \left[\left\langle |\mathbf{v}^n_\perp|^2 \right\rangle - \langle \mathbf{v}_\perp \rangle^2 \right] + b \left[\sigma^n_\parallel \right]^2}{\left[\frac{m}{\mu} - 1 \right]} \tag{3}$$

$$\sigma^2_\perp = \frac{g \left[\left\langle |\mathbf{v}^n_\perp|^2 \right\rangle - \langle \mathbf{v}_\perp \rangle^2 \right] + h \left[\sigma^n_\parallel \right]^2}{\left[\frac{m}{\mu} - 1 \right]} \tag{4}$$

$$\sigma^2_T = \frac{\left[\left\langle |\mathbf{v}^n_\perp|^2 \right\rangle - \langle \mathbf{v}_\perp \rangle^2 \right] + \left[\sigma^n_\parallel \right]^2}{\left[\frac{m}{\mu} - 1 \right]} \tag{5}$$

with

$$\langle \overrightarrow{\omega_g} \rangle = \frac{e \langle \mathbf{B} \rangle}{mc} \tag{6}$$

$$\langle \omega_r \rangle \simeq \frac{\mu}{m} \nu_c \,. \tag{7}$$

$\mathbf{v}$ and $\mathbf{v}^n$ are the ion and neutral velocity with σ^2 and $[\sigma^n]^2$ their respective dispersion. m, μ, $\langle \omega_r \rangle$, $\langle \overrightarrow{\omega_g} \rangle$ and ν_c are the ion mass, the reduced mass, the relaxation rate, the mean ion gyrofrequency vector and the (mean) collision rate. Under the assumption that the neutral flow consists mainly of molecular hydrogen and has a mean molecular mass $A_n = 2.3$, we get $a \simeq 0.16$, $b \simeq 0.67$, $g = 1 - a$ and $h = 1 - b$. We refer the reader to Houde et al. (2000a) and Houde et al. (2000b) for more details.

The importance of the presence of the magnetic field can be best visualized through Figure 1 where the effective velocity of an ion is plotted against the mean magnetic field strength for cases where the field direction is perpendicular to the neutral flow. As can be seen, the ion will not follow the neutral flow and will be captured by a magnetic field of relatively weak intensity (a few μG at a density n of 5×10^6 cm^{-3}) resulting in a lower effective velocity for the ion. The field intensities needed for this effect to come through are much lower than what is typically measured in molecular clouds (Crutcher et al. 1999).

If we further assume that the line profiles that are observed in the core of molecular clouds arise from a large amount of such flows (possibly of different orientations), we then arrive to the following three conclusions:

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

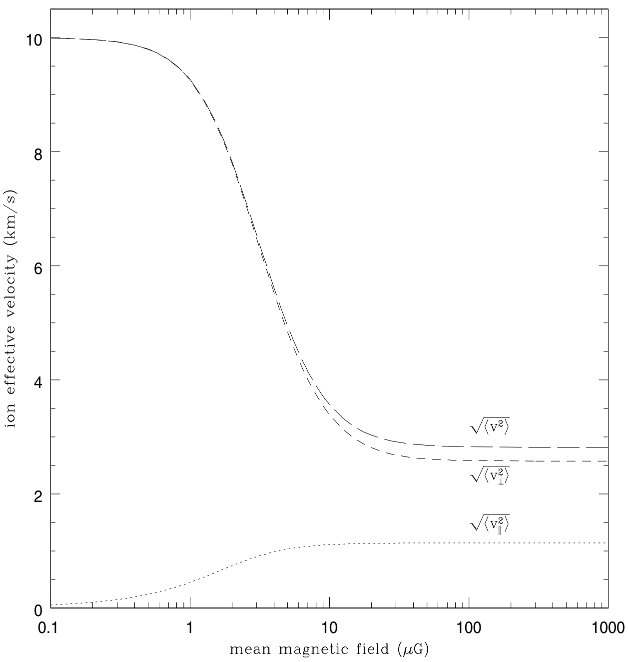

Figure 1. Ion effective velocity ($\langle \mathbf{v}_{\parallel}^2 \rangle^{\frac{1}{2}}$, $\langle \mathbf{v}_{\perp}^2 \rangle^{\frac{1}{2}}$ and $\langle \mathbf{v}^2 \rangle^{\frac{1}{2}}$) as a function of the mean magnetic field strength when $\mathbf{v}_{\parallel}^n = 0$, $|\mathbf{v}_{\perp}^n| = 10$ km/s, $n = 5 \times 10^6$ cm^{-3} and $A_i = 29$. From Houde et al. (2000a).

1. Coexistent ion and neutral species will have similar line profiles when there is a good alignment between the mean magnetic field and the neutral flows.
2. We can expect that in the core of molecular clouds, molecular ions would, in general, exhibit narrower line profiles than coexistent neutral species when there is some misalignment between the mean magnetic field and the neutral flows.
3. The narrowing of molecular ion lines will only happen when $\langle \mathbf{v}^n \rangle \neq 0$.

These three predictions have been verified observationally and the results were presented in Houde et al. (2000a), Houde et al. (2000b) and Houde et al. (2001). We are, however, more concerned here with our second assertion and, to this effect, we present in table 1 line width ratios obtained for fifteen molecular clouds. As can be seen, the ion species generally exhibit a narrower profile than the corresponding neutral species (in this case HCO^+ is compared to HCN and $H^{13}CO^+$ to $H^{13}CN$).

2. Relative line widths and mass dependency.

Under the assumption of a simple geometry for the observed sources (e.g., a bipolar outflow), it is possible to make some calculations regarding the expected line width ratios for individual sources or sample of objects.

First, for a given object, we can calculate what the minimum line ratio should approximately be. This will happen when the magnetic field is oriented in a direction perpendicular to the line of sight. We get in such cases (Houde et al. 2001):

$$\frac{\sigma_{obs}}{\sigma_{obs}^n} \simeq \left[\frac{g}{\left[\frac{m}{\mu} - 1\right]} \right]^{\frac{1}{2}} \simeq 0.25\,,$$

for a comparison of $H^{13}CO^+$ and $H^{13}CN$, with σ_{obs} and σ_{obs}^n the line widths of the ion and neutral species respectively (as expressed by their standard deviation from the mean velocity). Referring to table 1, we note this number corresponds quite well to the minimum ratio observed in our sample (0.22 for OMC-1 and 0.27 for OMC-2 FIR 4).

Second, it is possible to detect a mass dependency from the spectra of different ion species obtained for a single object. This can be seen from a study of equations (1)-(7) where we find that, under the assumption of coexistence, different ion species will have line profiles that exhibit:

- similar widths when the flows are aligned with the mean magnetic field
- widths following a $\left[\frac{m}{\mu} - 1\right]^{-1}$ mass dependency when the flows are perpendicular to the direction of the mean magnetic field.

These two extremes are plotted in Figure 2 along with line widths measurements (H_3O^+ and HCS^+ normalized to that of $H^{13}CO^+$) obtained for different objects. Coexistent species should have line widths that lie in between the two curves plotted in Figure 2. A certain amount of scatter is to be expected as all species will not be coexistent in most sources, but a mass dependency seems to emerge even with the small amount of data available at this time. FIRST, with its ability to detect lines from low-mass ion molecular species (e.g., H_2D^+, CH^+ and H_3O^+), will allow us to better verify this aspect of our model.

Finally, in some cases, the expected average ratio of the ion to neutral line widths for a given sample of molecular clouds can also be calculated. For example, if we assume that the neutral flows are randomly oriented (with a uniform distribution) with respect to the direction of the mean magnetic field, we find (Houde et al. 2000b):

$$\left\langle \frac{[\sigma_{obs}]^2}{[\sigma_{obs}^n]^2} \right\rangle \simeq \frac{1}{3} \left[1 + \frac{2}{\frac{m}{\mu} - 1} \right]\,, \tag{8}$$

which equals 0.38 (0.72, 0.47, 0.37) for an ion of molecular mass $A_i = 30$ (4, 11, 45). For the sample of objects from the previous table we find that:

$$\left\langle \frac{\sigma^2_{\mathrm{H^{13}CO^+}}}{\sigma^2_{\mathrm{H^{13}CN}}} \right\rangle = 0.41\,,$$

which is in good agreement with the value calculated above. But more importantly, we again see from equation (8) that a mass dependency is expected when comparing the line width ratios using different ion species.

Source	Coordinates (1950) RA	DEC	v (km/s)	⟨ratio⟩ thick	thin
W3 IRS 5	$2^{h}21^{m}53^{s}.3$	$61^{\circ}52'21''.4$	-38.1	0.43	0.39
GL 490	$3^{h}23^{m}38^{s}.8$	$58^{\circ}36'39''.0$	-13.4	0.61	...
HH 7-11	$3^{h}25^{m}58^{s}.2$	$31^{\circ}05'46''.0$	8.4	1.02	...
NGC 1333 IRAS 4	$3^{h}26^{m}05^{s}.0$	$31^{\circ}03'13''.1$	8.4	0.32	...
L1551 IRS 5	$4^{h}28^{m}40^{s}.2$	$18^{\circ}01'41''.0$	6.3	0.89	...
OMC-1	$5^{h}32^{m}47^{s}.2$	$-05^{\circ}24'25''.3$	9.0	0.19	0.22
OMC-3 MMS 6	$5^{h}32^{m}55^{s}.6$	$-05^{\circ}03'25''.0$	11.3	0.51	0.48
OMC-2 FIR 4	$5^{h}32^{m}59^{s}.0$	$-05^{\circ}11'54''.0$	11.2	0.76	0.27
NGC 2071	$5^{h}44^{m}30^{s}.2$	$00^{\circ}20'42''.0$	9.5	0.93	0.64
NGC 2264	$6^{h}38^{m}25^{s}.6$	$09^{\circ}32'19''.0$	8.2	0.85	0.88
M17 SWN	$18^{h}17^{m}29^{s}.8$	$-16^{\circ}12'55''.0$	19.6	0.90	0.81
M17 SWS	$18^{h}17^{m}31^{s}.8$	$-16^{\circ}15'05''.0$	19.7	0.90	0.78
DR 21(OH)	$20^{h}37^{m}13^{s}.0$	$42^{\circ}12'00''.0$	-2.6	0.80	0.69
DR 21	$20^{h}37^{m}14^{s}.5$	$42^{\circ}09'00''.0$	-2.7	0.98	0.58
S140	$22^{h}17^{m}40^{s}.0$	$63^{\circ}03'30''.0$	-7.0	0.80	0.85

Table 1. Ion to neutral width ratios in star forming regions. The ratios labeled as "thick" are obtained from the ratio of HCO^+ *to HCN line width and those labeled as "thin" from the ratio of* $H^{13}CO^+$ *to* $H^{13}CN$ *line width.*

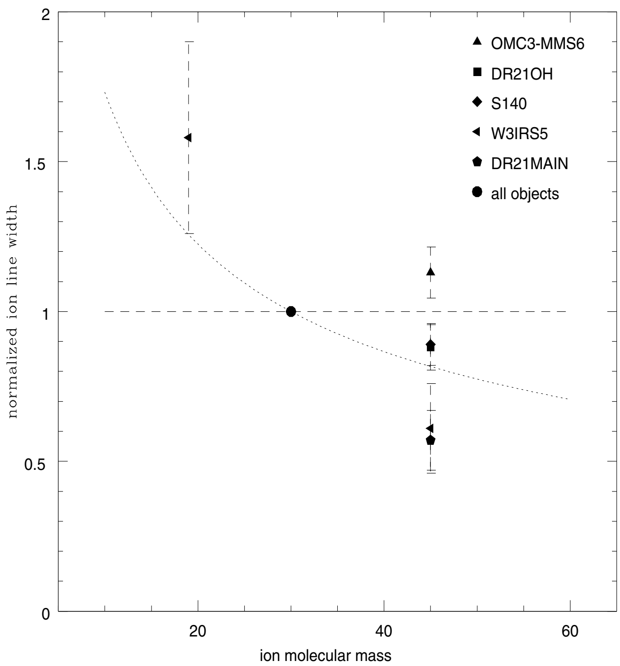

Figure 2. Ion line width as a function of the molecular mass. The line width is normalized to that of $H^{13}CO^+$ ($A_i = 30$) *for the cases where the neutral flows are aligned (straight broken line) or perpendicular (dotted curve) to the the direction of the mean magnetic field. The* H_3O^+ *detection in W3 IRS 5 is taken from Phillips et al. (1992).*

We again emphasize the fact that because of its frequency coverage, FIRST will allow us to study low-mass ion molecular species that are otherwise difficult or even impossible to observe with ground-based telescopes. It will then become possible to verify the applicability of our model to such molecular species and test the mass dependencies predicted and presented above.

3. Summary.

We have discussed a new approach to the problem of the detection of the magnetic field in the core of molecular clouds and showed how and why the manifestation of its presence can be observed in the line profiles of molecular ion species. The main conclusions reached were:

1. Coexistent ion and neutral species will have similar line profiles when there is a good alignment between the mean magnetic field and the neutral flows.
2. We can expect that in the core of molecular clouds, molecular ions would, in general, exhibit narrower line profiles than coexistent neutral species when there is some misalignment between the mean magnetic field and the neutral flows.

Moreover, because of the fact that in the presence of a strong enough magnetic field, the ions will resist in taking part in the flow motion (reduction of their mean velocity) and be forced into gyromotions about the magnetic field direction, there will be an increase in their velocity dispersion and their line width will, therefore, be a function of the mass of the ion. It will then be possible to use FIRST to observe lower mass molecular ions such as H_2D^+, CH^+ and H_3O^+ to test and verify this mass dependency. A few lines of choice are presented in table 2, the H_2D^+ line at 1370.15 GHz is currently in a frequency range not covered by FIRST. Hopefully, this will no longer be the case upon the commissioning of FIRST.

References

Crutcher, R. M., Troland, T. H., Lazareff, B., Paubert, G., and Kazès, I. 1999, ApJ, 514, L121

Species	Freq. (GHz)	n_c (cm^{-3})
H_2D^+	1370.15	10^6
CH^+	835.07	10^6
CH^+	1669.16	10^7
H_3O^+	984.70	10^7
H_3O^+	1665.81	10^7

Table 2. A few low-mass ion molecular lines which could be detected with FIRST. n_c stands for the critical density of the transition.

Houde, M., Bastien, P., Peng, R., Phillips, T. G., and Yoshida, H. 2000a, ApJ, 536, 857

Houde, M., Peng, R., Phillips, T. G., Bastien, P., and Yoshida, H. 2000b, ApJ, 537, 245

Houde, M., Phillips, T. G., Bastien, P., Peng, R., and Yoshida, H. 2001, ApJ, 547

Phillips, T. G., van Dishoeck, E. F., and Keene, J. B. 1992, ApJ, 399, 533