藉由分子譜線偏振探測恆星形成區內的磁場結構

楊智軒、賴詩萍
國立清華大學

摘要

一般藉由觀測塵埃偏振來測量磁場的主要問題是無法分辨視線方向上的磁場結構。然而由於每道分子躍遷都有其特定的臨界濃度，因此測量分子譜線的偏振－Goldreich-Kylafis 效應(GK效應)－提供了一種獨特的方法來探測恆星形成區核心的三維結構。儘管目前很難觀測到GK效應，阿塔卡瑪大型毫米及次毫米波陣列(ALMA)將很有機會執行GK效應的觀測。爲了要探討使用ALMA來觀測GK效應的可行性，我們開發了一套軟體來計算分子譜線在均勻磁場及速度梯度下的偏極化。此程式藉由大速度梯度近似，解出多躍遷輻射傳輸方程式在平行和垂直磁場方向的解，並預測每個躍遷的偏振百分比及方向。這裡我們展示在不同溫度、速度梯度幾何結構和分子雲密度的情況下，一氧化碳(CO)、一硫化碳(CS)及一氧化矽(SiO)等分子在高能階躍遷的結果。藉由這個軟體，我們將可以估計使用ALMA探測磁場幾何形狀時特定躍遷的偏極化量值。

Probing the magnetic field structure in star-forming regions through molecular line polarization

Louis Yang, Shih-Ping Lai
National Tsing Hua University

Abstract

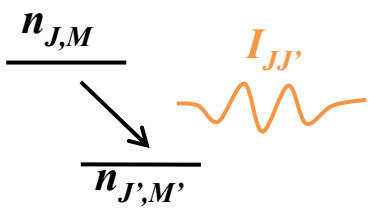
The major problem of the most commonly used method for probing magnetic fields, the dust polarization observation, is that it is incapable of differentiating the field structure along the line of sight. Since every molecular transition has a particular critical density, measuring the molecular line polarizations, the Golreich-Kylafis effect (GK effect), provides a unique way to probe the three-dimensional structure in star-forming cores. Although currently it is very difficult to measure GK effect, the Acatama Large Millimeter/submillimeter Array (ALMA) will potentially enable routine observations of GK effect. In order to investigate the feasibility of the GK effect observations with ALMA, we develop a computer program for modeling molecular polarization with uniform magnetic field and velocity gradient. The program solves the radiative transfer equations for multiple transitions in the direction parallel and perpendicular to the

magnetic field under the large velocity gradient approximation, and predicts the polarization percentage and direction of every transition. Here we demonstrate the results for CO, CS and SiO molecules in high-level transitions at different temperature and with different velocity gradient geometry and molecular cloud density. With this program, we can estimate the polarization of specific molecular transition for probing the magnetic field geometry with ALMA.

1. Introduction

It has become widely recognized that star formation cannot be fully understand without considering magnetic fields. Unfortunately, due to the extremely high sensitivity requirement, magnetic field structure in star-forming regions is so poorly measured to fairly validate the mainstream theories.

One way to decide the magnetic field inside the molecular cloud is to observe the polarization of its radiation. The linear polarization may present when the magnetic field and velocity gradient exist in the molecular cloud. The reason is that the magnetic field gives a specific direction for the molecule, and the anisotropy of velocity makes the optical depth for radiation to propagate also anisotropic. With the anisotropic radiation, the populations of the magnetic substates (M) will be unequal. Thus, the linear polarization radiation is enhanced. This effect was suggested by Goldreich and Kylafis (1981, 1982; also Kylafis 1983), and it provides us a way to probe the direction of magnetic field through linear polarization. The purpose of our work is not only to decide the direction of the magnetic field but also to search for better channel for observing this effect.



2. Basic Equations

The equations of radiative transfer are

$$\frac{dI^q_{JJ'}}{d\pi^q_{JJ'}} = -\phi(v)\left(I^q_{JJ'} - S^q_{JJ'}\right), \qquad q = \perp, \parallel$$

where I is the intensity, S is the source function, τ is the optical depth, q denotes the polarization, and JJ' denotes the transition from J to J'.

The rate equations describe the transition rate from one state to another. For each state, the transition comes from two parts, the radiative transition and the collision. When all transition comes to equilibrium, the total rate dn/dt will be zero. The rate equations are (Deguchi & Watson 1984)

$$0 = \frac{dn_{JM}}{dt} = -\sum_{\substack{J',M' \\ J'<J}} P_{JMJ'M'} + \sum_{\substack{J',M' \\ J'>J}} P_{J'M'JM} + \sum_{J',M'} \left(C_{J'M'JM} n_{JM} - C_{JMJ'M'} n_{JM}\right)$$

where $P_{JMJ'M'}$ denote the radiative part and $C_{JMJ'M'}$ denote the collisional rate.

The radiative contribution comes from three parts: absorption, stimulated emission and spontaneous emission. The radiative transition rate is

$$P_{JMJ'M'} = A_{JMJ'M'}\left[n_{JM} + R^{\Delta M}_{JJ'}\left(n_{JM} - n_{J'M'}\right)\right],$$

$$R^0_{JJ'} = \frac{3c^2}{2h\nu^3}\int \frac{d\Omega}{4\pi}\left[I^{\parallel}_{JJ'}(\theta)\sin^2\theta\right],$$

$$R^1_{JJ'} = \frac{3c^2}{4h\nu^3}\int\frac{d\Omega}{4\pi}[I^{\perp}_{JJ'}(\theta)+I^{\parallel}_{JJ'}(\theta)cos^2\theta],$$

where A is the Einstein A-coefficient and θ is the angle between the propagation direction and the z axis (the direction of B field).

LVG approximation gives a way to simplify the equations. It assumes that there is a large velocity gradient such that each photon that was emitted along this gradient direction is hard to be absorbed again since Doppler Effect makes its frequency different. This approximation gives an optical depth that will depend on geometry. For 1D velocity gradient along z axis,

$$\tau^q_{JJ'}(\theta) \propto \frac{k^q_{jj'}(\theta)}{cos^2\theta} \quad (1)$$

For 2D velocity gradient along the x-y plane,

$$\tau^q_{JJ'}(\theta) \propto \frac{k^q_{jj'}(\theta)}{\sin^2\theta} \quad (2)$$

For a cone like velocity gradient (mixing model between 1D and 2D) (Cortes *et al.* 2005),

$$\tau^q_{JJ'}(\theta) \propto \frac{k^q_{jj'}(\theta)}{\alpha\sin^2\theta+\cos^2\theta} \quad (3)$$

where α is the mixing parameter ($\alpha << 1$ for 1D).

With LVG approximation, the simplified solution for radiative transfer equation is

$$I^q_{JJ',excess} = (S^q_{JJ'} - \frac{1}{2}B_{JJ'})(1 - e^{-\tau^q_{JJ'}})$$

where B represents the cosmic background radiation (at T = 2.725K).

3. Method

In order to calculate the intensity of two polarizations in each level, we need to first calculate the population of each state. With the population, we can get the source function and, hence, the intensity of the radiation. However, the rate equations which can gives us the population have also dependences on intensity of radiation. So it becomes a nonlinear system for n_{JM}. The way to solve it is as follow:

1. Calculate the population n_{JM} in thermal equilibrium condition without any radiation present.
2. Calculate the intensity of the radiation by using the population n_{JM} that we just get.
3. Use the intensity of radiation from step 2 to recalculate the population n_{JM}.
4. Use the population n_{JM} from step 3 to redo step 2 to 3 until the population n_{JM} converges.
5. Calculate the final intensity $I_{JJ'}{}^q$ for two polarizations and get the fractional polarization $P_{JJ'}$.

4. Comparison

We compare our results to Goldreich & Kylafis' (1981) and Deguchi & Watson's (1984) to check our program. In these calculations, the lines of sight are perpendicular to z axis.

The slightly difference may come from the numerical error. Otherwise, our results agree well with previous.

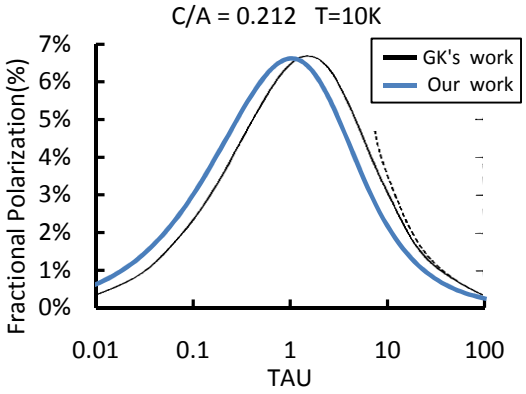


Fig. 1. Comparison of the two level calculation with that of GK for CO (1->0) transition in the 2D geometry.

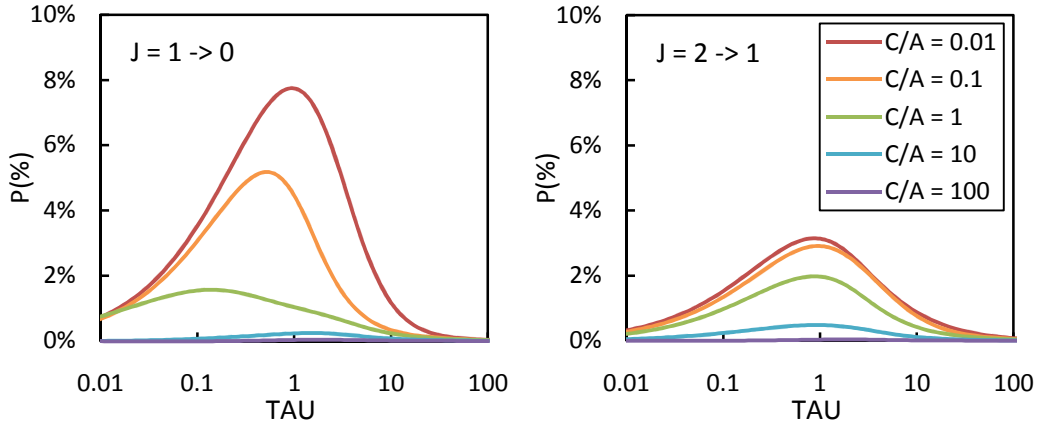


Fig. 2. Fractional polarization P for the CO transitions J = 1 -> 0 and 2 -> 1 at T = 30K in the 2D geometry. The calculation includes 5 levels.

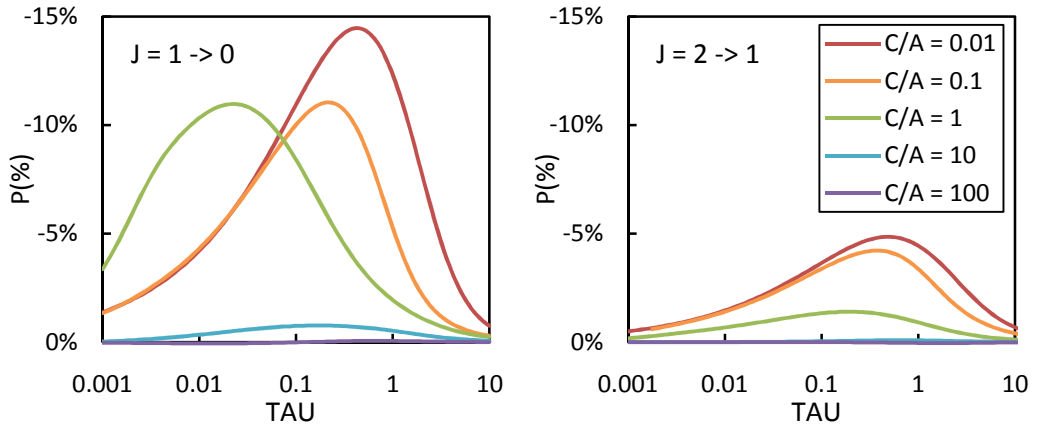


Fig. 3. Fractional polarization P for the CO transitions J = 1 -> 0 and 2 -> 1 at T = 30K in the 1D geometry. The calculation includes 5 levels.

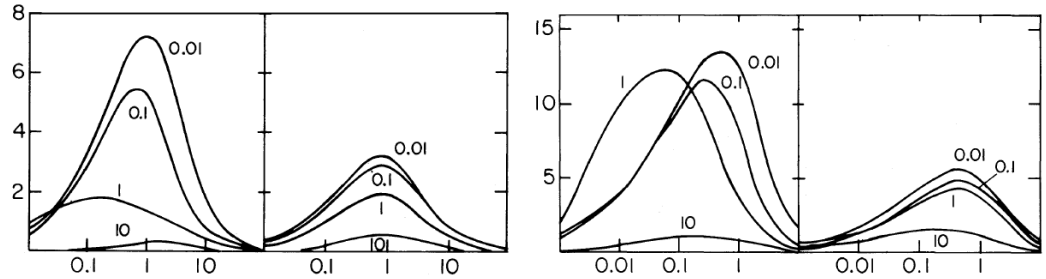


Fig. 4. DW's results of CO at T = 30K

5. Application: Outflow

We consider an ideal cone like geometry with α = 0.1 in equation (3), which corresponding to velocity gradient mainly along the z axis (1D-like) and some along the x-y plane (2D-like), to simulate the situation of outflow. We demonstrate some results of molecular transitions that are now observable (frequency around 300 GHz). The viewing angle here are θ = 90° to the direction of outflow (z axis) if no specify.

In SiO case, we choose J = 8 -> 7 transition at temperature T = 100K and compare the behavior of 1D and cone like geometry (Fig. 5). Also, the different viewing angles are considered. The results of CO(3 -> 2) and CS(8 -> 7) are shown in Fig. 6 and 7.

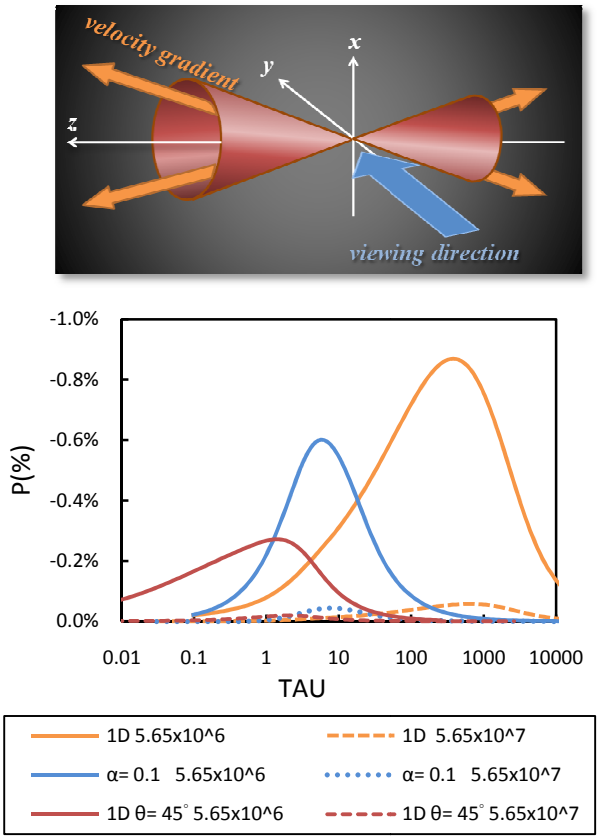


Fig. 5. Fractional polarization for SiO (8 -> 7) at T = 100K in high density region (n = 5.65×106 and 5.65×107 cm-3).

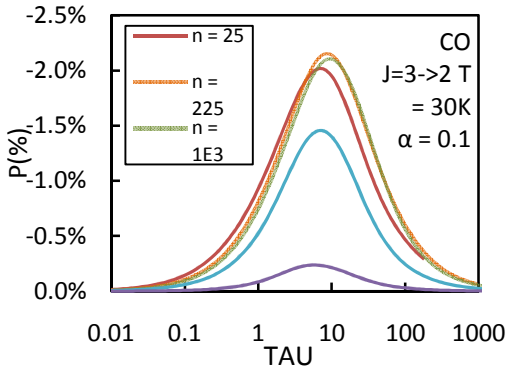


Fig. 6. Fractional polarization for CO (3 -> 2) at T = 30K with α = 0.1.

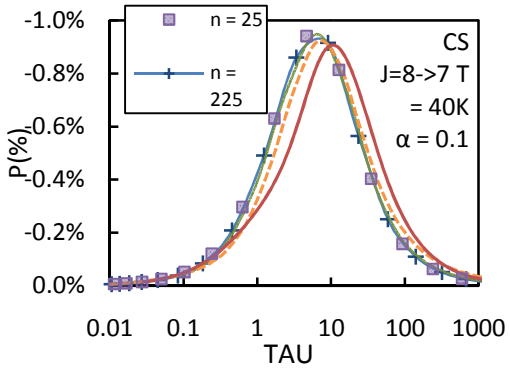


Fig. 7. Fractional polarization for CS (8 -> 7) at T = 40K with α = 0.1.

6. Discussion

In Fig. 5, the result for SiO J = 8 -> 7 transition at T = 100K shows that it is hard to observe the polarization for purely 1D geometry viewing perpendicular to it since the polarization peak is located at optical thick. The same transition in cone like geometry (α = 0.1) and 1D geometry with viewing angle θ = 45° are more possible to be observed.

In Fig. 6, the results for CO J = 3 -> 2 shows that there are appreciable polarizations when hydrogen density is lower than 10^3. For density higher than that, the polarizations are small.

In Fig. 7, the fractional polarizations for CS J = 8 -> 7 are almost the same for all density regions (25 cm^{-3} ~ 10^6 cm^{-3}). And the maximum is about 1% before TAU = 10.

The difference of polarization amounts between different types of molecule will allow us to construct the magnetic field structure of different density region through different types of molecule.

Reference

Cortes, P. C., Crutcher, R. M., & Watson, W. D. 2005, *ApJ*, 628, 780.

Deguchi, S., & Watson, W. D. 1984, *ApJ*, 285, 126.

Goldreich, P. & Kylafis, N. D. 1981, *ApJ*, 243, L75.

Goldreich, P. & Kylafis, N. D. 1982, *ApJ*, 253, 606.

Kylafis, N. D. 1983, *ApJ*, 267, 137.