# **Interstellar magnetic fields**

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### 1 Interstellar magnetic fields

In this lecture I will cover some of the physical processes that are central to studies of magnetic fields in the interstellar medium (ISM), and the related techniques developed and used for their characterization. The field of research centred on this topic have significantly evolved in recent years and, as a consequence, not all techniques can be covered in a single lecture; we will therefore focus on a few from the more commonly used.

### 1.1 The Stokes parameters

Most (but not all) studies of interstellar magnetic fields involve the measurements of polarization either in spectral lines or in continua (e.g., from dust or charged particles). It will therefore be beneficial to first consider how polarization states are modelled before investigating the different physical processes responsible for polarized signals and the techniques used in subsequent analyses.

We consider the propagation of electromagnetic plane waves and define two waves propagating in the same direction **n** with

> $\mathbf{E}_1 =$  $\mathbf{E}_2$   $=$  $B_i =$





## Outline

- Polarization and Stokes parameters
- Polarization from spectral lines
	- Zeeman effect
	- Goldreich-Kylafis effect
- Polarization from dust
	- Differential absorption
	- Emission
- Polarization in the radio
	- o Synchrotron
	- $\circ$  Faraday rotation, depolarization and B field strength
- Davis-Chandrasekhar-Fermi equation
- Dispersion analysis

#### Stokes parameters  $C$ <sup>2</sup> are complexed the superposition of the superpos interpreted as a single wave characterized by a total electric field E (x*, t*) stokes parameters quantities. If we define these amplitudes, using equations (1.4) and (1.12), as

 $\mathbf{E}(\mathbf{x},t)=(\mathbf{e}_1E_1+\mathbf{e}_2E_2)\,e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}.$ 

 $E_j = a_j e^{i \delta_j}$ 

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<sup>2</sup> *<sup>a</sup>*<sup>2</sup>

#### Stokes parameters  $C$ <sup>2</sup> are complexed the superposition of the superpos interpreted as a single wave characterized by a total electric field E (x*, t*) stokes parameters  $S + \alpha$ lige noromatore

 $\mathbf{E}\left(\mathbf{x},t\right)=\left(\mathbf{e}_{1}E_{1}+\mathbf{e}_{2}E_{2}\right) e^{i\left(\mathbf{k}\cdot\mathbf{x}-\omega t\right)}$  $E_j = a_j e^{i \delta_j}$  $\vec{E}$  =  $\vec{E}$  =  $\vec{E}$  =  $\vec{v}$  ( $\vec{k}$   $\cdot$   $\vec{x}$   $\sim$   $\omega t$ )  $y = (c_1 L_1 + c_2 L_2)$ .  $\mathcal{L}_j = u_j e^{-\mathcal{L}}$ 



$$
I = |\mathbf{e}_1 \cdot \mathbf{E}|^2 + |\mathbf{e}_2 \cdot \mathbf{E}|^2
$$
  
\n
$$
= a_1^2 + a_2^2 \qquad (1.17)
$$
  
\n
$$
Q = |\mathbf{e}_1 \cdot \mathbf{E}|^2 - |\mathbf{e}_2 \cdot \mathbf{E}|^2
$$
  
\n
$$
= a_2^2 - a_1^2 \qquad (1.18)
$$
  
\n
$$
U = 2 \operatorname{Re} [(\mathbf{e}_1 \cdot \mathbf{E})^* (\mathbf{e}_2 \cdot \mathbf{E})]
$$
  
\n
$$
= 2 a_1 a_2 \cos (\delta_2 - \delta_1)
$$
  
\n
$$
V = 2 \operatorname{Im} [(\mathbf{e}_1 \cdot \mathbf{E})^* (\mathbf{e}_2 \cdot \mathbf{E})]
$$
  
\n
$$
= 2 a_1 a_2 \sin (\delta_2 - \delta_1)
$$
  
\n(1.20)

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#### Stokes parameters  $E(x,t)=(e_+E_+ + e_-E_-) e^{i(k\cdot x - \omega t)}$ *E*<sup>+</sup> =  $\sqrt{2}$  $\frac{1}{2}$  $(1 - iE_2)$ *E* =  $\sqrt{2}$  $\frac{1}{2}$  $(1 + iE_2)$ e<sub>2</sub> Just as the unit vectors (e1*,* e2*,* n) form a basis for a plane wave, an alternative basis  $\mathbf{E}(\mathbf{x},t) = (\mathbf{e}_+ E_+ + \mathbf{e}_- E_-) e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}$  $e_{\pm} =$ 1  $\overline{\sqrt{2}}$  $(e_1 \pm i e_2)$  $F_{\rm tot} = \frac{1}{(E_{\rm tot} - iE_{\rm e})}$ **∀** *∠*  $\frac{1}{2}$  **·**  $\frac$ and any vector, such as the electric vector, such as the electric vector, can be written using the electric vector,  $\sim$  $E_{+}$  = 1  $\overline{\sqrt{2}}$  $(E_1 - iE_2)$  $E_{-}$  = 1  $\overline{\sqrt{2}}$  $(E_1 + iE_2)$

<sup>E</sup> (x*, t*)=(e+*E*<sup>+</sup> <sup>+</sup> <sup>e</sup>*E*) *<sup>e</sup>i*(k*·*x!*t*) (1.12) SOFIA school - 2023

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### This result shows that the Stokes parameter *U* is indeed measure of linear polarization and subsets of  $\overline{S}$





which, using our definitions for the Stokes parameters  $\mathcal{C}$  ,  $\mathcal{C}$  ,

#### Stokes parameters - linear polarization warranted assumption, we can express the polarized component of the electric field as Ep (x, tokes narameters - line; which, using our definitions for the Stokes parameters  $\mathcal{C}(\mathcal{C})$  , yields  $\mathcal{C}(\mathcal{C})$  , yields  $\mathcal{C}(\mathcal{C})$

 $\mathbf{E}_{p}\left(\mathbf{x},t\right)=E_{p}\left(\mathbf{e}_{1}\cos\theta+\mathbf{e}_{2}\sin\theta\right)e^{i\left(\mathbf{k}\cdot\mathbf{x}-\omega t\right)}$ *Q* (*1*) *D* (1.41) *A* (*2*) *J* (2007)

*p* =

SOFIA school - 2023 these pseudo-vectors do not behave like normal vectors. For example,

polarization fraction and angle the polarization fraction (or percentage, or level) *p* and the polarization angle  $\sum_{i=1}^{n}$ polarization fraction and angle

$$
p = \frac{\sqrt{Q^2 + U^2}}{I}
$$
\n
$$
\theta = \frac{1}{2} \arctan\left(\frac{U}{Q}\right). \tag{1.44}
$$



$$
Q = I_p \cos(2\theta)
$$
\n
$$
U = I_p \sin(2\theta)
$$
\n(1.41)\n(1.42)

#### Stokes parameters - linear polarization  $\rho$  =  $\frac{1}{2}$  (1.43)  $\mathcal{L}$ llnear *.* (1.44)

The combination of these two parameters lend themselves well to the notion of a **polar**ization (pseudo-)vector, where the length of the vector is set by *p* and its orientation (which is not a direction) by  $\theta$ . One must, however, by careful with this analogy because these pseudo-vectors do not behave like normal vectors. For example,

 $\mathbf{F}_{\mathbf{p}}$  finally, the pointing is generally defined such  $\mathbf{F}_{\mathbf{p}}$  and  $\mathbf{F}_{\mathbf{p}}$ 

- level *p* and orientated perpendicular to one another cancel out.
- averaged, not  $p$  and  $\theta$ .

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 $\overline{\mathfrak{c}}$ • Although  $p$  and  $\theta$  lend themselves well for certain types of analysis, it is important to remember that *Q* and *U* are the fundamental quantities that should be manipulated for calculations performed at the fundamental level. For example, if two sets of polarization measurements made on the same source are to be combined to, say, improve the signal-to-noise ratio, then it is the *Q* and *U* parameters that must be

• two polarization measurements yielding the same level *p* and orientations differing by  $\pi/2$  do not add up to give a total vector of length  $\sqrt{2}p$  and of intermediate orientation. Instead equations (1.41)-(1.42) make it clear the resulting polarization pseudo-vector will be of length  $p = 0$  since  $\cos(2\theta) + \cos(2\theta + \pi) = \sin(2\theta) +$  $\sin(2\theta+\pi)=0$ . In other words, polarization pseudo-vectors exhibiting the same *1 Interstellar magnetic fields*



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**Exercise**  $\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$  (CO)) with rotational states  $|J, m\rangle$  defined by the quantum numbers *J* and *m*, with  $\begin{vmatrix} 1 & 1 & -J \end{vmatrix}$  The electronic and vibrational ground states such that we are only dealing with pure rotational transitions. A transition  $|J,m\rangle \rightarrow |J+\Delta J,m+\Delta m\rangle$  will be allowed for cases Let us consider the case, for example, of a simple molecule (e.g., as carbon monoxide  $J \leq m \leq J$  in steps of 1. We will assume, for simplicity, that the molecule is in



#### Polarization from spectral lines *1 Interstellar magnetic fields* averaged, not *p* and • Finally, the polarization angle is generally defined such ✓ = 0 when pointing north

 $\Rightarrow$  *Individual spectral lines from atoms or molecules are intrinsically polarized, but...*  $\Leftarrow$ on the sky and is increasing eastward (0 ✓ ⇡).

#### Polarization from spectral lines - alignment the polarization state of a given spectral line depends on the value *m*, the change in the magnetic than the magnetic precisely. More precisely, a so-called the more is the precisely of the *i*-line  $\alpha$ and a -line whenever *m* = *±*1 (i.e., there are two of them).

• The atoms/molecules under question are endowed with a magnetic moment. Certainly, this will be the case for molecules to soon be discussed within the context of the Zeeman effect (e.g., HI, OH and CN) since, as we will see, the frequency splitting at the heart of this effect comes from a magnetic dipolar interaction. However, even other molecules weakly sensitive to the Zeeman effect (e.g.,  $CO$ ,  $CS$ ,  $H_2O$ , ...) will also have a small magnetic moment due to the rotation of their nuclei (and

• If the magnetic moment  $\mu$  and the ambient magnetic field strength  $B$  are such that  $\mu B/\hbar > \nu_{\text{coll}}, A_{ul}, B_{ul}I$ , with  $\nu_{\text{coll}}$  the collisional rate and  $A_{ul}$  and  $B_{ul}I$  the spontaneous and stimulated emission rates, then the molecules will be effectively aligned by the magnetic field. This condition usually easily met in a wide range of environments. For example, for molecules like CO we  $\mu/\hbar \sim 1$  mH/ $\mu$ G while at a density of, say,  $n \sim 10^4 \text{ cm}^{-3}$  and a relative collision velocity of  $\Delta v \sim 1 \text{ km/sec}$  $\nu_{\text{coll}} \approx n\sigma \Delta v \approx 10^{-6} \text{ s}^{-1}$  (i.e.,  $\sigma \sim 10^{-15} \text{ cm}^2$ ), as well  $A_{ul} \sim 10^{-6} \text{ s}^{-1}$  for CO  $(J = 2 \rightarrow 1)$ . That is, even a weak magnetic field of  $B \sim 10 \,\mu\text{G}$  will easily meet

A group of atoms or molecules must somehow be aligned in order to exhibit detectable polarized emission (or absorption) from a given spectral line, i.e., their symmetry axis must have a preferential orientation in relation to some external agent. An ambient magnetic field pervading the region within which the atoms/molecules are located will serve such a purpose, as long as a few conditions are met:

- their "slipping" from the electrons).
- this condition.

• The  $\pi$ -line (when  $\Delta m = 0$ ) only emits linearly polarized radiation aligned with the external magnetic field and a radiation pattern perpendicular to it. For example, an observer detecting emission from a  $\pi$ -line when the external magnetic field is confined to the plane of the sky would see the corresponding spectral line as being linearly polarized in the same direction as the field. On the other hand, the  $\pi$ line would not be detected if the magnetic field was (anti-)parallel with the line of sight. At intermediate orientation for the magnetic field, the radiation from the  $\pi$ -line would be polarized along the orientation of the projected magnetic field on the plane of the sky.

• Radiation from the  $\sigma$ -lines (when  $\Delta m = \pm 1$ ) is generally elliptically polarized, with their common linear polarization component perpendicular to that of the  $\pi$ line (i.e., perpendicular to the orientation of the projected magnetic field on the plane of the sky). The two  $\sigma$ -lines have, however, opposite circular polarization states (i.e., right for  $\Delta m = +1$  and left for  $\Delta m = -1$  when the field is pointing at the observer, and vice-versa). The detected polarization for a given  $\sigma$ -line is purely linear when the magnetic field is confined to the plane of the sky and purely circular (anti-)parallel with the line of sight.

in) frequency, then their polarization pseudo-vectors will cancel out because there

$$
\begin{array}{c}\n \overrightarrow{y} \\
 \overrightarrow{y}\n \end{array}
$$





### Polarization from spectral lines - alignment lines all have different polarization characteristics as well as radiation patterns in relation m snectral lines – al



#### Polarization from spectral lines - alignment  $\epsilon$  circular (anti-)parallel with the line of sight. Given the polarization properties and radiation properties and radiation patterns, as well as well as well as w

 $\Rightarrow$  *Individual spectral lines from atoms or molecules are intrinsically polarized, but...*  $\Leftarrow$ close relation to the orientation of the external magnetic field, one might external magnetic field, one might expect that it is not more might expect that it is not more might external magnetic field, one might expect th  $s$  from alones of molecules are maraisteally polarized, out...  $\leftarrow$ 

• At thermodynamic equilibrium both  $\sigma$ -lines have the same intensity and their total  $\frac{1}{2}$  intensity equals that of the  $\pi$ -line. If all these lines happen at the same (or are close<br>in frequency, then their polarization pseudo-vectors will cancel out because there the electronic and vibrational ground that with the electronic potations with called because in the such that with the such that with the such that with the such that we are only dealing with the such that we are also with **rotation**  $\bullet$  *j*  $\$ in) frequency, then their polarization pseudo-vectors will cancel out because there would then be an equal intensity or radiation in perpendicular radiation states (see then end of Sec. 1.1). The lack of a polarization signal implies the impossibility of

ization signals are opposite (i.e., orthogonal) no net polarization can be detected  $\sum_{i=1}^{\infty} a_i$  ization signals are opposite (i.e., orthogonal) no net polarization can be detected whenever these lines fall at the same (or are close in) frequency. Under these con-<br>ditions we cannot expect to learn anything concerning the line of sight component  $\begin{bmatrix} \text{arrows} \\ \text{arrows} \end{bmatrix}$  and  $\begin{bmatrix} \text{arrows} \\ \text{arrows} \end{bmatrix}$  of the magnetic field ditions we cannot expect to learn anything concerning the line of sight component







*H*  $\hat{H}$ = *H*  $\hat{H}$ = *H*  $\hat{H}$ 

*<sup>z</sup>B,* (1.49)  $(1.49)$ 

#### $\Delta F_s = \mu_B mR$  $(1.50)$  $e^{\frac{1}{2}t}$  $\Delta E_{\ell,m} = -\mu_B mB.$  (1.50)

#### Spectral lines - external magnetic field 2*m*<sup>e</sup> *.* (1.48) We now transition to the quantum world and write *H* ˆ = *H* ˆ <sup>0</sup> *µ* ˆ *·* B

We therefore find that the energy of the system is altered by a quantity that is proportional to the magnetic quantum number *m* and the external magnetic field. This

is a very important example as it clearly shows that the 2` + 1 times degeneracy of the

implies that a spectral line associated with the principal quantum number  $\alpha$  should be principal quantum number  $\alpha$ 

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 $\hat{\mu}$  · **B**  $\frac{\mu}{b}$  $\frac{d^2D}{\hbar}L$  $\hat{\bar{L}}$  $H \;\; = \;\; H_0 - \hat{\boldsymbol{\mu}} \cdot \mathbf{B}$  $a_n = \hat{H}_a + \mu \hat{B} \hat{T}_B$  $\hbar$  the eigenvalue, say,  $\hbar$  that the interaction with the magnetic with the magnetic with the magnetic with the magnetic  $\hbar$  *H*  $\hat{H}$ = *H*  $\hat{H}$ = *H*  $\hat{H}$ 

implies that a spectral line associated with the principal quantum number  $\alpha$  should be principal quantum number  $\alpha$ 

*<sup>z</sup>B,* (1.49)  $(1.49)$ 

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#### We therefore the system is alternative find the system is alternative that is proportional to the magnetic quantum number *m* and the external magnetic field. This *|*`*, m*i state is lifted by the presence of the magnetic field. For an atom or molecule, this implies that a spectral line associated with the principal  $\blacksquare$ split into 2` + 1 separate fine structure lines. This is the so-called normal Zeeman  $\mathcal{L}$ Degeneracy is lifted!

is a very important example as it clearly shows that the 2` + 1 times degeneracy of the

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 $\hat{\mu}$  · **B**  $\frac{\mu}{b}$  $\frac{d^2D}{\hbar}L$  $\hat{\bar{L}}$  $H \;\; = \;\; H_0 - \hat{\boldsymbol{\mu}} \cdot \mathbf{B}$  $a_n = \hat{H}_a + \mu \hat{B} \hat{T}_B$  $\hbar$  the eigenvalue, say,  $\hbar$  that the interaction with the magnetic with the magnetic with the magnetic with the magnetic  $\hbar$ 

#### Spectral lines - Zeeman effect replaced by the nuclear magnetic in that equation). For this reason, the main spectral  $\frac{1}{100}$ lines  $\frac{7}{2}$ eman effect in the I (OH) and cyanid (CN), which all have *S* = 1*/*2.

Before we look more closely at some candidate spectral lines, let us look at what can be expected as far as solving our frequency degeneracy problem. The Zeeman sensitivity associated with these spectral transitions is on the order of  $1 \text{ Hz}/\mu\text{G}$ . Looking on the high-side of magnetic field strengths we can expect  $B \sim 1$  mG in the denser parts of giant molecular clouds. That is, the **Zeeman splitting** between the  $\pi$ - and  $\sigma$ -lines will be  $\Delta\nu_z \sim 1$  kHz. On the other hand, line of sight velocities measured for these spectral lines can often reach as high as tens of  $km/s$ . Using the Doppler shift formula we find

We can therefore already see that, although  $\pi$ - and  $\sigma$ -lines will not fall on the same frequency for a given line of sight velocity, there will be significant spectral overlap between them. This effect, which gets worse with increasing frequency, will strongly limit the applicability of the Zeeman effect for measuring the magnetic field strength. For example, while the Doppler broadening would be on the order  $\sim$  5 kHz with  $\Delta v = 1$ km/s for the commonly used OH lines at 18 cm, it would become  $\sim$  376 kHz for the CN er broadening would be on the

where  $\nu_0$  and  $\Delta v$  are the frequency of the spectral transition and its line width, respectively.

 $(N = 1 \rightarrow 0)$  transition at 113 GHz.

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that

$$
\Delta\nu \approx 3.3 \left(\frac{\nu_0}{1 \text{ GHz}}\right) \left(\frac{\Delta v}{1 \text{ km s}^{-1}}\right) \text{ kHz},\tag{1.52}
$$

### polarization states: linear polarizations along e<sup>1</sup> and e<sup>2</sup> for *Q* (see equation 1.18) and aport and the 45 - Zeeman effect and entire contract and under the U (see Equation 1.34) such a set of  $\sim$ polarizations along e<sup>+</sup> and e for *V* (see equation 1.24). Whenever ⌫*<sup>z</sup>* ⌧ ⌫ Taylor Spectral lines - Zeeman effect

with  $\theta$ , as before, the polarization angle on the plane of the sky (relative to  $e_1$ ) and  $\iota$  the inclination angle of the magnetic field relative to the line of sight (Crutcher et al. 1993,

$$
Q \simeq -\frac{1}{4} \frac{d^2 I}{d\nu^2} (\cos \theta - \sin \theta) (\Delta \nu_z \sin \nu)^2
$$
\n
$$
U \simeq -\frac{1}{4} \frac{d^2 I}{d\nu^2} (\sqrt{2} \sin \theta) (\Delta \nu_z \sin \nu)^2
$$
\n
$$
V \simeq \frac{dI}{d\nu} \Delta \nu_z \cos \nu,
$$
\n(1.55)

ApJ, 407, 175). It follows that



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$$
\n
$$
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$$
\n
$$
V \simeq \frac{dI}{d\nu} \Delta \nu_z \cos \iota,
$$
\n(1.55)

ApJ, 407, 175). It follows that

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• The Stokes *V* spectrum is proportional to the first frequency derivative of the total

# HI 21 cm - Zeeman effect

H I and OH gas are shown in Figures  $B_{los} = -100 \pm 13 \mu G$ ely. The  $\sim$  15 km s<sup>-1</sup> H | I  $B_{\text{los}}$  component also about a factor of  $2^2$  wider than the OH This suggests that the H  $\vert$  I  $B_{\text{los}}$  component shocked gas while the OH does not. tion ( $\sim$  20") molecular emission data from he M17 SW core as  $B_71/\sqrt{N}$  is scarce. The emission ( $\sim$  47" resolution; Wilson et al. Figure 7 extends this far north, but it is B-17N is a separate  $^{13}$ CO clump at this.  $N$  does appear to be spatially coincident n edge of the Rainey  $\bar{e}$  at. (1987) CO(3-2) n has velocities ranging from 14 to 18 km et al. UKIRT data have  $\rightarrow$  55" resolution, is note that the position of " $F$ " S CO peak increasing velocity in agreement with  $\Phi$ ig. 11).

#### 3.4.4. OH  $B_{\text{los}}$  in B-17C

ion B-17C is also shown in Figure 11. The cant  $B_{\text{los}}$  detections and high-OH column  $B-17C$  is roughly spherical with a size of ge magnetic field measured in  $\bullet$ H toward  $\pm$  50  $\mu$ G. This OH condensation appears to only one narrow velocity component at with a  $\Delta v_{\text{FWHM}} \sim 2.5$  km s<sup>-1</sup>% A similar<sup>10</sup> is also observed in  ${}^{13}CO$  toward this region SOFIA school - 2023 **Ondensation is**  $\vert$   $\cup$ 



<sup>Ð</sup>t. The <sup>Ð</sup>tted value of and its calculated error are given at the top of the <sup>B</sup>los

 $\alpha$  within the range  $2.7$ –1 expected for ETE line stre zero to infinite line optical depth; the one that is no<br>RI all lines only very slightly too weak for LTE an  $\text{OH}$  18 cm  $\text{g}^{\text{RI}}$  dept  $\text{J}^{\text{lines}}$  only very slightly too weak for LTE and  $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{1}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{2}{9}$   $\frac{$ tical depth. The maximum line optical depth found by nique is  $\tau \approx 0.5$ . We therefore compute the column the  $N = 0$  state assuming the  $RI = 10$  lines are optically *inc iv – U state as*<br>*I ALLE 170 Gee Turner & Gan* (see Turner & Gammon  $1975$ ). We then compute the  $2A$  H I AND OH TOWARD M17  $\frac{OH}{B}$  tos  $=$  150  $\mu$ mn density of CN in all states by assuming that all excited with an assumed excitation temperature of 25 in Figures  $10b$ are warm, dense cores, and several of the  $T_A^*$  are not to  $T_{A}^*$ .  $B<sub>los</sub>$  component  $\log_{10}$  25 K in strength.) We then assume CN/H<sub>2</sub> = 4 er than the OH order to find  $N_{CN}(H_2)$ . This value of  $CN/H_2$  is consistent  $B_{\text{los}}$  component. those found by Turner & Gammon (1975) in dense  $\frac{3}{2}w$ . des not. sion data from and matches the results found in OMC1 cores  $\mathbb{R}$ . Hatenes ene is scarce. The et al. (2003). Finally, we compute the observed ma ; Wilson et al. $0.5$ of the CN Zeeman sources from the radii and geome  $-0.5$ orth, but it is of  $N_{h,r}(H_2)$  and  $N_{CN}(H_2)$ , denoted  $N_{23}(H_2)$  in the following. clump  $at<sup>T</sup>$  this also list for comparison the virial masses  $M_{\text{vir}} = 210$ ally coincident where *r* is expressed in pc and  $\Delta v$  in km s<sup>-1</sup>.  $I=(RCP + LCP)$ 1987)  $CO(\frac{3}{2}-2)$  $I = (RCP \times LCP)$ As an example of the data, Fig. 1 shows the spectra  $\frac{1}{2}$  $m$  14 to 18 km 55" resolut<del>io</del>n, W3OH. The Stokes *I* spectrum is the average (weight  $\overline{1}$  GP<sup>'</sup>  $f \cdot F$  "s CO peak" sengtivity to the Zeeman effect) of hyperfine lines  $1, \xi$  $V = (RCP - LCP)$ ment with our <sub>02</sub> (Table 1); these are the lines that have significant sen the  $\chi$  equivalent effect. The Stokes *V* spectrum is the equivalent age, where the non-Zeeman contributions to the obser to gain imbalance and instrumental polarization (coeff Figure 11. The and  $\mathfrak{C}_2$  in the fitting equation (Sect. 2)) have been  $\mathbf{\vec{w}}$ m h-OH column W3OH the instrumental polarization contribution to S with a size of the equivalent of a 5.6 mG Zeeman signal for a (totally in OH toward.02  $Z_{\rm H} = 1$ , Hz/ $\mu$ G for all 7 hyperfine components. Hence, ion appears to FIG. 13.—OH  $B_{\text{los}}$  fit toward  $\overline{\text{OH}}$  condensation B-17C at positon lostion lostion results of  $B_{\text{los}}$  at positon results of  $B_{\text{los}}$  at  $B_{\text{los}}$  and  $B_{\text{los}}$  and  $B_{\text{los}}$  and  $B_{\text{los}}$  and  $B_{\text{los}}$  and  $B_{\text$  $\frac{1}{2}$  condensation  $B^{-1}$   $\subset$  at position in this case is abo  $\Gamma_{3}$ , component at 18<sup>h</sup>17<sup>m</sup>26<sup>s</sup>, -16°11′00″. The upper panel shows the VtIA Stokes P profile  $s^{-1}$ . A similar (solid histogram), and the bottom parel at town the MeAt stroke E equation is gnal. Only the large  $\Re$ Figure 1.5: Sultural and *(solia histogram)*, and the bottom-pare are medicine in the universe of the large was a<br>and this region and *(solid histogram*) with the fitted derivative of Stokes Lshown as a smooth means that h (solid histogram) with the fitted derinative of Stokes I shown as a smooth  $\mu$  ative of Stokes L shown as ra smooth among the hyperfine components  $\mu$  $\text{School}$  -  $2023$  live. The solid portroms of the Stokes I histogram (upper pape 2023 irve. The solid portions of the Stokes I histogram (upper panel) SOFIA school - 2023 $\mid$  SOFIA sch $\mid$  $\mu$  of the corresponding to the contract of the pullets  $B_{\text{los}}$  results from Cl and the Series of the Series of the Country of the vertex of the vertex of the velocity range in the velocity o

<mark>ard this region</mark>



and random spectral noise. We then fitted the result test what signal-to-noise ratio was required to ach  $\mathbf{S}$  stronger magnetic field magnetic field  $\mathbf{S}$  is shown in  $\mathbf{S}$  and  $\mathbf{S}$  is shown in  $\mathbf{S}$  is s



Courtesy T. Troland, adapted from Crutcher et al. 2010, ApJ, 725, 466.

# **Spectral lines - Zeeman effect & masers**<br>
<u>*Interstellar magnetic field*<br> **1996** AM.</u>



Figure 1.8: Detection of the Zeeman effect in OH  $(2\Pi_{3/2}, J = 7/2, F = 4^+ \rightarrow 4^-)$  lines in the W3(OH) molecular cloud complex. The combination of narrow spectral lines ( $\Delta v \approx 0.3 \text{ km s}^{-1}$  or  $\approx 13 \text{ kHz}$ ) and strong *total* magnetic fields ( $B \simeq$ 7.6 – 10.6 mG) resulted in a clear Zeeman splitting  $\Delta \nu_z \simeq 6-8.4$  kHz. From Güsten, Fiebig and Uchida 1994, A&A, 26, L51.

ulated than those responsible for *m* = 0.

# **Spectral lines - Zeeman effect & masers**<br>  $\frac{10000}{\frac{11000}{RBC}}$



Figure 1.8: Detection of the Zeeman effect in OH  $(2\Pi_{3/2}, J = 7/2, F = 4^+ \rightarrow 4^-)$  lines in the W3(OH) molecular cloud complex. The combination of narrow spectral lines ( $\Delta v \approx 0.3 \text{ km s}^{-1}$  or  $\approx 13 \text{ kHz}$ ) and strong *total* magnetic fields ( $B \simeq$ 7.6 – 10.6 mG) resulted in a clear Zeeman splitting  $\Delta \nu_z \simeq 6-8.4$  kHz. From Güsten, Fiebig and Uchida 1994, A&A, 26, L51.



*"… a bow-shock model in which the magnetic field is compressed in the cooled post-shock layer preceding the compact HII region. "*

### Polarization from spectral lines - Goldreich-Kylafis

- Most molecules/transition  $\rightarrow$  no Zeeman effect
	- $O$  E.g., CO is more than 1000 times less sensitive to Zeeman than CN
- $\bullet$   $\pi$  and  $\sigma$ -lines will fall at the same frequency
- How to get linear polarization?
	- $O$  Move away from thermodynamics equilibrium because the πand σ-lines will cancel each other
	- $\circ$  Anisotropy will bring linear polarization (no circular polarization)
		- E.g., velocity gradient or increased optical depth along magnetic field, anisotropic external radiation field, ...
	- $\circ$  No information on magnetic field strength
	- 90 deg ambiguity



Cortés+ 2021, ApJ, 923, 204





RA (ICRS)

### Polarization from spectral lines - Goldreich-Kylafis



# Spectral lines - Goldreich-Kylafis + masers

### Measuring magnetic fields from water masers in the synchrotron protostellar jet in W3(H<sub>2</sub>O)

C. Goddi<sup>1, 2</sup>, G. Surcis<sup>3, 4</sup>, L. Moscadelli<sup>5</sup>, H. Imai<sup>6</sup>, W. H. T. Vlemmings<sup>7</sup>, H. J. van Langevelde<sup>3, 8</sup>, and A. Sanna<sup>9</sup>

SOFIA school - 2023

Goddi et al. 2017, A&A, 597, A43





# Spectral lines - Goldreich-Kylafis + masers



central component, the synchrotron jet, and two (western and eastern) secondary components (see Sect. 4.1 for an interpretation).

RIGHT ASCENSION (J2000)

Fig. 2. Magnetic field orientation (in the plane of the sky) for 17 individual masers with  $P_l < 5\%$  (red segment) and strength for four (nonsaturated) masers for which the Zeeman splitting was measured. The 8.4 GHz emission imaged with the VLA (beamsize  $\sim 0$ . 2) by Wilner et al. (1999) (yellow contours: corresponding to 0.02, 0.06, 0.1, 0.2, 0.3 mJy beam<sup>-1</sup>) is overplotted onto the 1.4 mm continuum emission mapped with the PdBI (beamsize ~ 0.  $\frac{1}{5}$ ) by Wyrowski et al. (1999) (gray scale and black contours: same as in Fig. 1). The radio continuum shows a main

### SOFIA school - 2023 | The Coloration of the Coloration of Goddi et al. 2017, A&A, 597, A43



### Spectral lines - Goldreich-Kylafis + masers



Fig. A.1. Total intensity (*I*, black solid line) and linear polarization intensity (red solid line) spectra of the  $H_2O$  maser features 012, 016, 036, 058, 063, and 128 (upper panel). The linear polarization intensity spectra have been multiplied by a factor of three for 036, 063, and 128. The linear polarization fraction (black solid line, left scale) and the linear polarization angle (dashed black line, right scale) are also shown (lower panel).



Fig. A.2. Total intensity (I, upper panel) and circular polarization intensity (V, lower panel) spectra for the  $H_2O$  maser features 037, 039, 063. SOFIA school - 2023 The thick red line shows the best-fit models of *I* and *V* emission obtained using the FRTM code (see Appendix A). The maser features are centered 597, A43

Goddi et al. 2017, A&A,





"wrong" internal align.





#### Polarization from dust - alignment mm/submm wavelengths has shown that radiation emanating from dust populations is also linearly polarized, albeit generally at 90 deg relative to that from background stars

- $\bullet\,$  Within the framework of RAT irregularities in the shapes of dust grains lead to a  $\bullet\,$ finite helicity which will serve to spin them up when irradiated by an external radi- $a_3$ ation field (we saw from equations 1.6 and 1.8 that an electric field can be expressed with two orthogonal circularly polarized states, which will scatter differently off the Grain's body frame grains because of their helicity).
- Once a grain is spinning it will tend do so by minimizing its total energy while conserving its angular momentum, resulting in a rotation about its symmetry axis (i.e., the "short" axis, which has the maximum moment of inertia). This is the socalled internal alignment process, which is rendered possible through the Barnett effect where quantum mechanical unpaired spins (we are dealing with paramagnetic grains) flip to make up for the change in rotational angular momentum in the alignment process.
- Since the flipping of spins also brings about a net magnetization (there are initially as many pointing up than down), the grain will interact with the external magnetic field, resulting in its symmetry axis precessing about it.

### • SOFIA school - 2023

Just as was the case for molecules discussed earlier, a population of grains can only radiate globally with a net level of polarization if its constituents are somehow aligned with some external agent. Here again, the external magnetic field will fulfill this role. The leading theory for grain alignment is the so-called Radiative Alignment Torque (RAT) theory (Lazarian & Hoang 2007, MNRAS, 378, 910), and its main ingredients can be listed as follows:



 $\mathbf{\hat{a}}_{1}$ 

ω

 $\hat{a}_{2}$ 

 $\widetilde{\mathsf{L}_\mathsf{Bar}}$ 

 $\bullet$  In general, linear polarization from dust grain traces the orientation of the projection of the magnetic field on the plane of the sky.

 $\bullet$  At short wavelengths (e.g., in the optical) where polarization is due to differential absorption, the linear polarization is aligned with the magnetic field.

• The polarization level *p* is independent of the magnetic field strength (similar to the Goldreich-Kylafis effect but unlike the Zeeman effect) and varies proportionally



#### Polarization from dust - differential absorption  $T$ m duct  $\sim$  differential aheorntion more careful treatment would, however, corroborate the conclusions that: • In general, linear polarization from dust grain traces the orientation of the projecdust - dittorontial a  $\sim$  At short wavelengths (e.g., in the optical) where  $\sim$  in the optical) where  $\sim$  1.1  $\sim$  1.1  $\sim$



# Polarization from dust - differential absorption





### *1 Interstellar magnetic fields* Polarization from dust - differential absorption



Figure 1.13: Starlight polarization measurements over the sky. At low latitudes the inferred orientation of the magnetic field follows the Galactic plane. Courtesy T. J. Jones.

• At longer wavelengths (e.g., at FIR and  $\text{mm/summ}$  wavelengths) where the radi-<br>Least Likely ation emanates from the grains, the linear polarization vectors are oriented at 90 deg relative to that of the magnetic field.

• The polarization level p is independent of the magnetic field strength (similar to the Goldreich-Kylafis effect but unlike the Zeeman effect) and varies proportionally





#### Polarization from dust - emission  $\bullet$  duct amiccion from dust grapher  $\bullet$ tion of the magnetic field of the magnetic field of the plane of the plane of the plane of the second of the s



Figure 1.14: Cartoon showing the polarization showing the polarization of light emitted from dust grains. Because



![](_page_35_Figure_1.jpeg)

Figure 1.15: Polari**niquy** map of Sexpens South from SOEIA/HAWO+ at 214  $\mu$ m (emis- $\sigma$ sion; blue vectors) and with  $\text{SIRPQ}$  trip the near-infrared (H band) (differential absorption; grey vectors). Both sets of vectors show the orientation of the magnetic field on the plane of the sky. From Pillai et al. 2020, Nat.

![](_page_36_Figure_3.jpeg)

### Polarization from dust - differential absorption + emission  $\overline{1}$

![](_page_36_Figure_1.jpeg)

# Polarization from synchrotron radiation

- Radiation from acceleration  $-$  relativistic gyration about magnetic field
- For a single charge  $-$  elliptical polarization
- For a population of charges with a range of pitch angles  $(\alpha)$ 
	- $o$  relativistic beaming cancels circular polarization component

 $\rightarrow$  Polarization is linear and perpendicular to Bpos

Rybicki & Lightman - Radiative processes in astrophysics, 1979 (Wiley)

![](_page_37_Picture_11.jpeg)

![](_page_37_Picture_6.jpeg)

![](_page_37_Figure_9.jpeg)

• Propagation in plasma: birefringence to circular polarization modes/states

![](_page_38_Picture_7.jpeg)

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![](_page_38_Figure_8.jpeg)

 $\rightarrow$  Depolarization with a dependence on frequency

![](_page_38_Figure_2.jpeg)

• Rotation of linear polarization state

$$
\Delta\theta(\omega) = (k_{-} - k_{+})\frac{\Delta z}{2}
$$

- propagation time
	- with  $\text{DM} \equiv \int_0^{\infty} n dz \rightarrow$  dispersion measure *dt* p *dω*  $\simeq -\frac{4\pi q^2}{4}$ *mcω*<sup>3</sup> ⋅ DM Δ*z* 0  $ndz \rightarrow$
- Faraday rotation
	- with  $\text{RM} \equiv \frac{1}{2} \frac{1}{24} \left| \frac{1}{2} m B_{\text{los}} dz \right| \rightarrow \text{rotation measure}$ *d*(Δ*θ*) *dω* = *d dω*  $(RM \cdot \lambda^2)$  $RM \equiv$ *q*3 2*πm*2*c*<sup>4</sup> ∫ Δ*z* 0  $nB$ <sub>los</sub> $dz \rightarrow$

# Faraday rotation — magnetic field strength

- propagation time
	- with  $\text{DM} \equiv \left| \text{ } 1 \text{ rad} z \rightarrow \text{dispersion measure} \right|$ *dt* p *dω*  $\simeq -\frac{4\pi q^2}{4}$ *mcω*<sup>3</sup> ⋅ DM  $DM \equiv$ Δ*z* 0  $ndz \rightarrow$
- Faraday rotation
	- with  $\text{RM} \equiv \frac{1}{2} \frac{1}{24} \left| \frac{1}{2} m B_{\text{los}} dz \right| \rightarrow \text{rotation measure}$ *d*(Δ*θ*) *dω* = *d dω*  $(RM \cdot \lambda^2)$  $RM \equiv$ *q*3 2*πm*2*c*<sup>4</sup> ∫ Δ*z* 0  $nB$ <sub>los</sub> $dz \rightarrow$

# Faraday rotation — magnetic field strength

 $\langle B_{\text{los}} \rangle \simeq$  $2\pi m^2c^4$ *q*3 **⋅** 

![](_page_40_Picture_10.jpeg)

# Polarization from synchrotron radiation

### M<sub>5</sub>1

Fletcher+ 2011, MNRAS, 412, 2386

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![](_page_41_Figure_6.jpeg)

### VLA+Effelsberg & *λ*3 cm *λ*6 cm

### B field

### Analysis of polarization maps - DCF equation potential tential the strength of the strength of the strength of the dispersion of the dispersi polarization vectors. As long as a few assumptions and approximations are made...

The basic idea underlying the DCF-method consists of modelling the magnetic field with two components such that

#### $B = B_0 + B_t$  (1.58) *1 Interstellar magnetic fields*

where  $B_0$  and  $B_t$  are the large-scale (or mean or ordered) and turbulent (or random) parts of the overall field. We then assume that

- The turbulent component is weak, i.e.,  $B_t \ll B_0$ .
- The turbulent component is zero-mean, i.e.,  $\langle \mathbf{B}_t \rangle = 0$ .
- Deviations from the mean field are due to Alfvén waves, i.e.,  $\mathbf{B}_0 \cdot \mathbf{B}_t = 0$ .
- And there is equipartition between turbulent kinetic and magnetic energies, i.e.,  $\rho v_t^2/2 = B_t^2/8\pi.$

and recognizing that the polarization angle  $\Delta\theta = B_t/B_0$  we arrive at the DCF equation for the plane of the sky magnetic field strength

This last equation is readily transformed to

$$
v_t = \left(\frac{B_t}{B_0}\right) \left(\frac{B_0}{\sqrt{4\pi}}\right)
$$

![](_page_42_Figure_16.jpeg)

$$
B_0 = \sqrt{4\pi\rho} \frac{v_t}{\Delta\theta}
$$

Starting with Davis and Chandrasekhar & Fermi and for many decades afterwards,

It became clear early on that the technique had several shortcomings. For example, here are a few issues

- Turbulence in the ISM is not only due to Alvén waves (compressible modes exist).
- The mean field  $B_0$  must be fairly close to the plane of the sky.
- The assumption of weak turbulence (i.e.,  $\theta \ll 1$ ) is often violated.
- The measured signal is integrated along the line of sight and across the telescope beam, which artificially reduces the dispersion in  $\Delta\theta$  (and overestimates  $B_0$ ).

#### Analysis of polarization mans - DCF equation estimates of magnetic field strengths were obtained with this equation by calculating a Analysis of polarization maps - DCF equation

![](_page_43_Picture_6.jpeg)

![](_page_44_Figure_0.jpeg)

Tahani, 2022, arXiv:2203.11179v1).

![](_page_44_Picture_2.jpeg)

Figure 1.16: A combination of the Zeeman  $B_{\text{los}}$  measurements of Fig. 1.7 and a compilation of published estimates of the plane of the sky magnetic field strength *B*<sup>0</sup> obtained with the DCF equation. It appears that the DCF method consistently overestimates the magnetic field strength. From Pattle, Fissel  $\&$ 

![](_page_45_Figure_0.jpeg)

![](_page_45_Picture_2.jpeg)

#### well as other assumptions concerning the statistical properties of B0 and B<sub>t</sub>, it is it is a noncan be shown that equation (1.62) reduces to (Houde et al. 2016) reduces to (Houde et al. 2016, 162) reduces t Angular dispersion analysis

SOFIA school - 2023

is the number of turbulence cells probed by the telescope beam. Since both the turbulence correlation length  $\delta$  and the effective depth  $\Delta'$  of the region under study can be

$$
1 - \langle \cos \left[ \Delta \theta \left( \ell \right) \right] \rangle = \left[ \frac{1}{1 + N \langle B_0^2 \rangle / \langle B_t^2 \rangle} \right] \left[ 1 - e^{-\ell^2/2 \left( \delta^2 + 2W^2 \right)} \right] + \sum_{j=1}^{\infty} a_{2j} \ell^{2j}.
$$
 (1.63)

The last term on the right-hand side is a Taylor series representation for the contribution from the large scale (or mean) magnetic field, which can be readily fitted and removed from the data, while the other term is that due to turbulence. The quantity

$$
N = \frac{\left(\delta^2 + 2W^2\right)\Delta'}{\sqrt{2\pi}\delta^3} \tag{1.64}
$$

An example of such a dispersion analysis for the CS (*J* = 5 ! 4) data is presented in

# Angular dispersion analysis

![](_page_47_Figure_1.jpeg)

SOFIA school - 2023 RA (ICRS) Cortés+ 2021, ApJ, 923, 204

Figure 1.17: Dispersion analysis of the CS (*J* = 5 ! 4) polarization map presented in Cortés+ 2021, ApJ, 923, 204

along with the autocorrelated Gaussian beam (segmented curve), and the ALMA dirty beam (segmented), and the fit to the data, we deriv

#### Angular dispersion analysis excess width of the autocorrelation function beyond that of the telescope beam (black Angular dispersion analysis is a measure of the turbulence and the turbulence and the turbulence and the turbulence and turbulence a to be ' 0*.*42 arcsec or 2.6 mpc at the distance of NGC 6334 I(N) (1.3 kpc).

calculate the relative amount of turbulence in the magnetic field from

![](_page_48_Picture_2.jpeg)

U8 The value thus calculated  $(\sqrt{B_t^2})$  $\setminus$ */*  $\langle B_0^2$ 0  $\geq$  $\simeq 0.08$ ) is then inserted in the DCF equation with an average of the spectral line width ( $v_t \approx 5.3 \,\mathrm{km \, s^{-1}}$ ) to get a plane of the sky magnetic field strength of  $B_0 \simeq 2.8$  mG.

$$
\frac{\langle B_t^2 \rangle}{\langle B_0^2 \rangle} = N \left[ \frac{b^2 (0)}{1 - b^2 (0)} \right]
$$
  
\n
$$
\equiv (\Delta \theta)^2.
$$
 (1.66)

![](_page_48_Picture_4.jpeg)

The value for the number turbulence cells found to be  $N \simeq 1.4$  through equation (1.64) can be used with level at the peak of the autocorrelation function  $b^2$  (0)  $\simeq 0.06$  to

![](_page_49_Figure_1.jpeg)

44

![](_page_50_Figure_1.jpeg)

![](_page_51_Figure_1.jpeg)

![](_page_52_Figure_1.jpeg)

## Summary

- Measuring magnetic fields is difficult...
	- $\overline{O}$  Zeeman is the only direct measurement method but low SNR
		- better for masers
	- Polarization from spectral lines and dust are indirect and statistical  $methods \rightarrow \text{imprecise with DCF}$
	- Polarization at radio wavelengths  $\rightarrow$  synchrotron and Faraday rotation • Significant efforts to improve estimates (e.g., angular dispersion
	- analysis)
	- New techniques are being developed (Velocity Gradients Technique, Differential Measure, Anisotropic Resonant Scattering, ...)

 $O$  Hope to go beyond DCF

# Merci !

![](_page_54_Picture_1.jpeg)

![](_page_54_Picture_2.jpeg)

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# WA NSERC<br>WA CRSNG