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Astronomical Line Polarization Through Gas Transport

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Abstract Magnetic fields are critical to the dynamics of the interstellar medium (ISM), influencing star formation and interstellar gas dynamics. This paper explores a novel way to probe magnetic fields through molecular line polarization mechanism, that is based on the experimentally well-established Senftleben-Beenakker (SB) effect. In molecular line polarization through SB effects, gaseous transport processes such as viscous strain and thermal gradients, cause molecules to align through directional collisions, subsequently polarizing their emission lines. This polarization mechanism differs from the Goldreich-Kylafis (GK) effect, as it is not dependent on optical depth nor non-thermal excitation. We derive a theoretical framework to model molecular alignment due to the SB effect. We discuss the applicability of SB polarization as a tool to trace magnetic fields in turbulent media and accretion disks.

1 Introduction

Magnetic fields permeate the interstellar medium, shaping astrophysical dynamics. This work focuses on molecular interstellar media, that exist in gas condensations with densities of 100 to 10^9 cm^{-3}, and temperatures ranging from 10 to 1000 Kelvin. Although ionization fractions are low, collisional coupling transfers magnetic influence to neutral gas, significantly affecting dynamics, as magnetic energy can rival or exceed turbulent and thermal energy densities. Thus, measuring magnetic fields in molecular media is crucial for a comprehensive understanding of interstellar processes.

Magnetic fields in molecular media can be indicated through the observation of molecular line polarization. Molecular line emission is polarized to degrees of some per cents and is observable in the strongest emission lines. The origin of molecular line polarization is commonly attributed to the Goldreich-Kylafis (GK) effect [7]. The GK effect explains this polarization as arising from molecular excitation in an

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anisotropic medium, where the anisotropic radiation field aligns molecules. Molecular alignment is initially oriented in the direction of the radiation field anisotropy, but due to the precession of the molecule around the magnetic field, the alignment is re-oriented to the magnetic field direction. When magnetic precession is faster than other molecular interactions, emission polarizes parallel or perpendicular to the magnetic field. The GK effect is effective at near-unity optical depth and low gas densities, when radiative excitation dominates over collisions. The GK effect has been leveraged to trace magnetic fields towards (high-mass) star-forming regions, protoplanetary disks, the circumstellar envelopes of evolved stars, and molecular clouds in external galaxies.

Molecular alignment and subsequent line polarization can be induced not only by radiative processes but also by collisions [16, 25]. This study explores additional conditions under which directional collisions induce molecular alignment in an interstellar gas. To this end, we consider the experimentally well-established and characterized Senftleben-Beenakker (SB) effect [3, 23]. In the SB effect, fluids, that are under the influence of a magnetic field, acquire anisotropic transport properties. The anisotropies in the transport processes are the consequence of the molecular constituents of the fluid aligning along the transport direction, through directional collisions between particles that have anisotropic potential. The magnetic field impacts this process, as particles also precess around it. If this precession is fast compared to the collision time, then the alignment will be re-oriented to the magnetic field. In this way, molecular alignment along the magnetic field direction is retained, while it is effectively quenched in other cases. The resulting anisotropic transport coefficients, that are a function of the magnetic field strength divided by the pressure (i.e., the magnetic precession frequency divided by the collision frequency), have been well-characterized through experimental means for hydrodynamical transport tensors such as the viscosity tensor [13], and the thermal conductivity tensor [12], for a wide variety of molecules (for a full review, see [4, 21]). While tensor-anisotropies under magnetic fields is interesting from a fluid-dynamical perspective, their measurements have also served as experimental benchmarks for the testing of collisional modeling, specifically their dependence on the (anisotropic) intermolecular potential energy surfaces [10]. The large body of experimental and theoretical literature on the SB effect has been condensed in the monographs of Ref. [21].

Given the low densities of interstellar gas, where magnetic precession rates typically exceed collision rates [17], SB effects should be prevalent. Effectively, this means that under the influence of gaseous viscous strains, or thermal gradients, the molecular constituents of the gas should acquire alignment, leading to the polarization of their spectral lines. This paper investigates the conditions under which SB effects significantly and detectably polarize molecular emission. Molecular emission polarized through SB effects provides for a robust polarization mechanism that, in contrast to the GK effect, is not dependent on line optical depth, and does not require non-thermal excitation of the molecules. The molecular line polarization due to SB effects can be used as a robust tracer of the ambient interstellar magnetic field. In addition, it may also be possible to relate the line polarization due to SB effects to fluid dynamical properties of interstellar gases that cannot be measured otherwise.

This paper is built up as follows. In Sect. 2 we review the theory of alignment and polarization of molecules and their spectral lines. In Sect. 3, we discuss astrophysical processes conducive to SB effects and identify regions in the interstellar medium where anisotropic transport phenomena lead to significantly polarized line emission. Section 4 highlights potential limitations and model deficiencies. We conclude in Sect. 5.

2 Polarization and Alignment Due to the SB Effect

Due to the Senftleben-Beenakker (SB) effect, gas transport coefficients, of e.g. thermal transport or viscous strain, become anisotropic under the influence a magnetic field. The anisotropic transport properties are the result of alignment manifesting in the molecular constituents. Therefore, it is implicit in the theory of the SB effect, that a fluid also becomes birefringent under the effect of a directional flow. Leveraging this insight, Hess [8, 9] discussed the possibility to characterize the SB effect through experimental polarization observations, and in-so-doing derived the proper kinetic theory, starting from the Waldmann-Snider equations, of the alignment of molecules under directional flows.

We briefly revise concepts from the description of quantum molecular alignment, that are commonly applied to transfer of polarized line radiation in astrophysical gases. We assume that a molecule, with eigenstates of definite (total) angular momentum, j, precesses fast around a magnetic field, $\boldsymbol{B}$, which determines its symmetry axis: its eigenstates can be accurately described by the total angular momentum and its projection onto the magnetic field direction, $|jm\rangle$. We describe the molecular population in terms of its irreducible density matrix operator elements, $\hat{\rho}_{jk} = \sum_m \left[C^{j\ j\ k}_{m\ -m\ 0}\right]^2 |jm\rangle \langle jm|$, where the symbol $C^{j\ j\ k}_{m\ -m\ 0}$ is a Clebsch-Gordan coefficient. The rank of the irreducible tensor element, k, runs from 0 to $2j$. The $k = 0$ element is related to the total population of the quantum state j, while for $k > 0$, the elements of k which are even are commonly referred to as alignment elements, and those for which k is odd are referred to as the orientation elements. We note the expectation value of irreducible density matrix operator as $\rho_{jk} = \langle \hat{\rho}_{jk} \rangle$. The relative alignment and orientation of a specific quantum level we denote by $\sigma_{jk} = \rho_{jk}/\rho_{j0}$. Alignment is present in a population of molecules if their magnetic sublevels are populated unequally, but symmetrically, for levels with equal absolute projection, $|m|$. Orientation is present in a population of molecules if there is an imbalance between the population of magnetic sublevels of equal absolute projection $|m|$. Both alignment and orientation can be produced through collisions, yet in gaseous transport, alignment elements are more potently excited and accordingly have more effect on the transport properties [21]. Thus in the following, we set population elements, ρ_{jk}, of uneven k to zero: our molecules are aligned but not oriented.

We now discuss the transfer of radiation through an aligned molecular medium. We describe the propagation of radiation, with spectral energy flux density, $I_\nu(\hat{k})$ at frequency ν, in the direction $\hat{k}$. Since alignment of the molecules is with respect to the magnetic field direction, it is most advantageous to denote the transfer of radiation in the two polarization modes parallel and perpendicular to the magnetic field rejection onto the propagation direction, $\hat{e}_\parallel$ and $\hat{e}_\perp = \hat{k} \times \hat{e}_\parallel$. For brevity, we denote these $I_\parallel$ and $I_\perp$, dropping in the notation the dependence on frequency and direction. We are interested in the production of polarization, $p_l = [I_\parallel - I_\perp]/[I_\parallel + I_\perp]$, by the molecular medium. We consider the transfer of radiation at radio-to-millimeter frequencies, where radiation scattering is negligible, and astronomical observations of molecules are commonly made. In the optically thin limit, the polarization fraction of a transition between quantum states $j \to j-1$, that characterizes astrophysically common diatomic molecules, can be related to the degree of molecular alignment, and tends to [16, 19], $p_l \simeq -\frac{3}{4\sqrt{5}}\sqrt{\frac{(j+1)(2j+3)}{j(2j-1)}}\sigma_{j2}\ \sin^2\theta$, where $\cos\theta = \hat{k}\cdot\hat{b}$ is the projection of the radiation direction onto the magnetic field direction.

Reference [9] modeled the population of magnetic sublevels within a level j, which he denotes $N_{jm} = \langle |jm\rangle\langle jm|\rangle$, under the influence of a viscous strain. We restate equation (22) of Ref. [9] in terms of the relative alignment of the molecular quantum level, under the influence of a viscous strain $\sigma_{j2} = \sqrt{\frac{6j(j+1)}{(2j-1)(2j+3)}}\left[\frac{\eta}{p_0}\frac{\omega_{T\eta}}{\omega_\eta}\left(\hat{b}\cdot\overline{\nabla\boldsymbol{v}^T}\hat{b}\right)\right]$, where η and p_0 are the dynamical viscosity and pressure, and $\overline{\nabla\boldsymbol{v}^T}$ is the traceless symmetric part of the strain-rate tensor. The ratio $\omega_{T\eta}/\omega_\eta$ is a measure for the anisotropy of the interaction potential of the molecular collision complex. We can now derive the expected linear polarization fraction of an optically thin $j \to j-1$ transition, that is the result of the viscous strain in the gas that it traces, $p_l^\eta = -\frac{3}{4}\sqrt{\frac{6}{5}\frac{j+1}{2j-1}}\left[\frac{\eta}{p_0}\frac{\omega_{T\eta}}{\omega_\eta}\left(\hat{b}\cdot\overline{\nabla\boldsymbol{v}^T}\hat{b}\right)\right]\sin^2\theta$. In this way, we have related the polarization degree of line radiation that emerges from astrophysical gas, to the viscous strain in the direction of the magnetic field that this gas is under.

3 Astrophysical Conditions Leading to Viscous Polarization

Viscous dissipation of MHD turbulence. Turbulence is ubiquitous in the interstellar medium, and spans eight orders of magnitude from its driving scale to the viscous scale, where dissipation occurs. Given the complexity of turbulence, we take an order-of-magnitude approach to estimate its effects on molecular alignment and polarization. To estimate the polarization fraction due to turbulent strains, we focus on dissipation at the viscous scale, as at these scales, the internal states of the gaseous particles become excited. The dynamical viscosity scales as $\eta \sim \rho c_\mathrm{s}\ell_\mathrm{mfp}$, with the gas density, ρ, the sound velocity c_s and the mean-free-path of the molecular gas constituents, ℓ_mfp. The pressure scales as $p_0 \sim \rho c_\mathrm{s}^2$. Thus, the fraction $\frac{\eta}{p_0} \sim \frac{\ell_\mathrm{mfp}}{c_\mathrm{s}}$. Now, we specialize the viscous strain term, $\hat{b}\cdot\overline{\nabla\boldsymbol{v}^T}\hat{b}$, to a turbulent medium. At first glance, one would expect this term to average out to 0 in the case of isotropic turbulence; after all, the directional strain-rate of circular eddies averages to zero. However, it is well established that turbulence in the interstellar medium is magnetized, and therefore is anisotropic. Eddies are elongated in the direction along the magnetic field, $\ell_\parallel > \ell_\perp$, and their relative elongation increases going to lower scales. While the precise scaling relations are still under debate, a common result is the scaling of $\ell_\parallel \sim \ell_\perp^{2/3} L_{\rm inj}$ [2]. Thus, with such elongated eddies, the highest rate-of-strain, and thus the strongest alignment, is expected perpendicular to the magnetic field direction: $\hat{b} \cdot \overline{\nabla \boldsymbol{v}^T} \hat{b} \simeq -\frac{1}{2}\frac{v_\eta}{\ell_\eta}$, where v_η and ℓ_η are the expected velocity and dimension at the viscous scale. We estimate this fraction by order-of-magnitude. We assume that turbulence in the interstellar medium follows roughly two scaling regimes: above the sonic scale, turbulence follows a Burgers scaling, while below the sonic scale, we assume that turbulence follows a Kolmogorov scaling [22]. Adopting these scalings and extrapolating to the sonic scale, we find that the strain at the viscous scale can be expressed as $\frac{v_\eta}{\ell_\eta} \sim \frac{[\ell_\eta/\ell_{\rm s}]^{1/3} c_{\rm s}}{\ell_{\rm mfp}^{3/4}\ell_{\rm s}^{1/4}} \sim c_s[\ell_{\rm mfp}\ell_{\rm s}]^{-1/2}$. Now we can proceed to make an estimate for the polarization fraction that is due to anisotropic turbulent viscous dissipation. First for a general $j \to j-1$, transition, we find $p_l^{\eta,{\rm turb}} \sim \frac{3}{8}\sqrt{\frac{6}{5}}\frac{j+1}{2j-1}\frac{\omega_{T\eta}}{\omega_\eta}\sqrt{\frac{\ell_{\rm mfp}}{\ell_{\rm s}}}$. Now, specializing in $j = 1$, adopting $\omega_{\eta T}/\omega_\eta \sim 0.1$ [9], and using typical values from Ref. [22]: $\ell_{\rm mfp} \sim 10^{13}$ cm and $\ell_{\rm s} \sim 10^{17}$ cm, we obtain $p_l^{\eta,{\rm turb}} \sim 0.1\%$. Since $p_l^{\eta,{\rm turb}} \propto \ell_{\rm mfp}^{1/2}$, denser regions with shorter mean free paths should exhibit greater angular momentum polarization. Notably, such regions are also more influenced by gravitational forces, which can further enhance directional alignment, as we will explore in the next section.

In principle, all constituents of the interstellar medium should be impacted by turbulent angular momentum polarization, and exhibit polarization degrees of the order 0.1%. However, modern telescopes are sensitive to these low degrees of polarization only for those species that are associated with brightest emission lines, such as CO. We expect this polarization mechanism to be dominant when molecular lines are thermally excited, at densities above the critical density, when collisional transitions occur frequently with respect to the Einstein A-coefficient of the transition under investigation. For subthermally excited molecules, alternative polarization effects such as through the GK effect [7] likely dominate.

Viscous dissipation in the α-disk. The α-disk model was introduced by Ref. [24] as a theoretical model of an accretion disk around a compact object. In the α-disk, the transport of angular momentum, thus facilitating accretion, is due to so-called turbulent viscosity. Whereas for regular microscopic kinematic viscosity, $\nu \sim c_s \ell_{\rm mfp}$, turbulence can enhance this viscosity, when describing global processes that do not resolve the eddy-like motions that cause strains on smaller scales. In an accretion disk, the effective turbulent kinematic viscosity is thus parameterized according to its typical velocities and dimensions, as $\nu = \alpha c_s H$, where H is the disk scale height and $\alpha \leq 1$.

We restate the estimate of the polarization fraction due to viscous strain, putting in the proper relations according to α-disk theory of a thin accretion disk. For the ratio between the viscosity and the pressure, we put $\eta/p_0 \sim \nu/c_s \sim \alpha H/c_s$. Furthermore, in a thin disk, we have $H \sim c_s/\Omega_K$, where $\Omega_K = \sqrt{GM/R^3}$ is the Keplerian rate of rotation at radial distance R, around a compact object of mass M (G is the gravitational constant). We let the velocity field be fully Keplerian: $\left(\hat{b} \cdot \overline{\nabla \boldsymbol{v}^T} \hat{b}\right) \sim \Omega_K$. Then, the line polarization fraction of a $j \to j-1$ transition due to viscous strain in an α-disk is, $p_l^\alpha \sim -\frac{3}{4}\sqrt{\frac{6}{5}\frac{j+1}{2j-1}}\frac{\omega_{T\eta}}{\omega_\eta}\alpha$. This leaves us with a rather simple relation between the α-parameter, that is a proxy for the disk activity, and the polarization fraction for molecular lines excited in them. For a typical molecule possessing a dipole, we have $\omega_{\eta T}/\omega_\eta \sim 0.1$ for collisions with its main collision partner H_2. Typical estimates place α in the range $\sim 10^{-2} - 0.6$ [1]. Thus, for a $1 \to 0$ transition, we have $p_l^\alpha = 1.6\alpha$. For the most active accretion disks, $p_l^\alpha = 10\%$, while typical disks of $\alpha \sim 0.1$ yield polarization fractions $p_l^\alpha \sim 0.2\%$.

Protoplanetary disks. A protoplanetary disk forms around a low-mass protostar at the late stages of its formation. The physical conditions, dynamics, evolution and chemistry of the disk determine the environment where planets form. While α-disk prescriptions were popular in early modeling of protoplanetary disks, it is now believed that accretion processes in protoplanetary disks are mainly due to the launching of magnetically driven winds [20], even though the magnetic fields that would drive such winds have not been directly measured [15, 27]. The low levels of turbulence that have been observed towards a variety of protoplanetary disks [5] put stringent upper limits on the $\alpha \lesssim 10^{-2}$, making viscosity subdominant as an agent of angular momentum transport. Concurrently, it also puts an upper limit on the predicted angular momentum polarization due to viscous strain in an alpha disk, and constrains $p_l^\alpha \lesssim 0.1\%$. There have been deep observations to probe the polarized emission from protoplanetary disk molecules, which have yielded marginal detections of the polarized emission at the level of some percents for ^{12}CO and its main isotopologue ^{13}CO [26]. If real, such high polarization fractions cannot be the product of the angular momentum polarization due to SB effects, but instead are likely due to GK effects [17, 18].

Active Galactic Nuclei (AGN). Accretion disks around AGN are crucial for feeding supermassive black holes and influencing galaxy evolution. As an example of an AGN disk, we turn to the closeby active galaxy NGC 1068. While it has been attempted to fit the accretion disk of NGC 1068 to the mold of an α-disk, the α-disk model proved inconsistent as it implied strong gravitational instabilities. In an attempt to supersede the simple α-disk prescription, models that include gas clumpiness are favored [14]. At any rate, high-resolution ALMA observations show intricate dynamics towards the nuclear region of NGC 1068, with a flip in rotation direction in the inner disk [11]. Such dynamics are associated with very high degrees of shearing, that should be reflected in the angular momentum polarization of the molecular constituents. The site of the rotation flip should be associated with high polarization degrees of several per cents due to SB polarization in the thermal lines. SB polarization through gaseous transport should be dominant in dense gas where GK polarization is quenched through collisions. In this way, resolved polarization observations of thermal lines would offer a unique view of the magnetic fields of in the highly dynamic nuclear gas.

NGC 1068 belongs to a class of active galaxies that hosts strong water megamaser emissions. NGC 1068 is the first galaxy where water megamasers have been found to have polarized emission [6], which has lead to interesting constraints on the accretion dynamics in the innermost regions and its relation to magnetic fields. Water masers should be polarized to degrees $p_l^{\mathrm{H_2O}} \sim 3\% \left[\frac{\alpha}{0.1}\right] \left[\frac{\omega_{\eta T}/\omega_\eta}{0.1}\right] \left[\frac{\tau_{\mathrm{m}}}{10}\right]$, adopting representative values for α and $\omega_{\eta T}/\omega_\eta$ and the maser optical depth, τ_{m}. This mechanism of polarization is about as effective as through anisotropic pumping [19].

4 Model Assumptions and Parameters

We examined molecular alignment in astrophysical transport processes and its observability through polarized molecular line emission. Molecular alignment is a prerequisite for the Senftleben-Beenakker (SB) effect, where anisotropic transport coefficients arise under a magnetic field. This effect is well understood both experimentally and theoretically, emerging naturally from the Boltzmann transport equations when applied to rotating molecules. The specialization of these equations to rotational states, known as the Waldmann-Snider equations, requires assumptions for solvability. Typically, a near-equilibrium molecular distribution is assumed, with first-order corrections accounting for gas strains and thermal gradients. Anisotropic transport effects arise when molecular rotation interacts with a magnetic field, but the equilibrium assumption weakens as the Knudsen number increases. Experiments have validated SB effects, particularly by measuring anisotropic transport coefficients at moderately low Knudsen numbers [12, 13]. Reference [9] introduced polarization spectroscopy as a tool for characterizing SB effects, laying the theoretical foundation that this work builds upon. The degree of polarization can be linked to the Knudsen number: $\frac{\eta}{p_0} \overline{\nabla \boldsymbol{v}^T} \sim \mathcal{M} \frac{\ell_{\mathrm{mfp}}}{L} \sim \mathcal{M}$ Kn. The moderate polarization fractions that we predict puts Kn $\lesssim 1$, supporting the validity of our approach. However, since SB effects emerge at viscous scales, direct observations are beyond current telescope capabilities, and our estimates rely on extrapolation. If an observational experiment can be set up that pristinely traces SB polarization in a spectral line, this would yield a direct probing of gas motions at viscous scales.

Another key quantity in polarization estimates is the ratio $\omega_{\eta T}/\omega_\eta$, which strongly depends on the molecular species. Although the interstellar medium (ISM) is composed almost entirely of H2, its symmetric structure and high rotational constant make it difficult to observe. Radio astronomers therefore rely on tracer species like CO (with typical abundances of $\sim 10^{-4}$) to characterize the molecular ISM. This means that when considering the ratio $\omega_{\eta T}/\omega_\eta$, the relevant collision-complex is the one between the tracer species and H_2. While collisions between ISM molecules and H_2 are under active and ongoing investigation, the properties that are commonly extracted from these collision complexes are the state-to-state collisional transition rate coefficients. While the collision-complex anisotropy is an extremely relevant variable to these calculations, it's representation in the $\omega_{\eta T}/\omega_{\eta}$ factor is not commonly extracted and reported from the calculations. As such, no modern theoretical constraints on $\omega_{\eta T}/\omega_{\eta}$ for different ISM species exist. Similarly, experimental efforts have not been directed to constrain the transport properties of different molecules embedded in H_2 gases, as experimentalists have directed most of their attention to pure gases [21]. This leaves the ratio $\omega_{\eta T}/\omega_{\eta}$ largely unconstrained.

5 Conclusion

We have introduced a novel mechanism for molecular line polarization in astrophysical environments, through the theoretically and experimentally well established Senftleben-Beenakker (SB) effect. SB effects show that molecules that constitute a gas that is under viscous strains or thermal gradients, align themselves along the direction of gaseous transport. In environments such as interstellar media, due to the presence of magnetic fields, alignment is re-oriented to the magnetic field, and thus spectral emission from aligned molecules carries information on the magnetic field. In contrast to other mechanisms of interstellar molecular line polarization, such as through the Goldreich-Kylafis (GK) effect, line polarization due to SB effects does not require molecules to be excited subthermally, or excited under the influence of an anisotropic radiation field. Rather, line polarization due to SB effects require some gas strain to be present to be operative. Exploratory calculations suggest that gas strains due to turbulent dissipation can lead to polarization fractions of a fraction of a per cent, while the gas strain that is present in viscously evolving accretion disks can lead to molecular line polarization of some percents.

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