Draft version February 19, 2018
Preprint typeset using LaTeX style AASTeX6 v. 1.0

NON-ZEEMAN CIRCULAR POLARIZATION OF MOLECULAR SPECTRAL LINES IN THE ISM

M. A. Chamma[1], M. Houde[1], J. M. Girart[2] and R. Rao[3]
[1]Department of Physics and Astronomy, The University of Western Ontario, London, ON, N6A 3K7, Canada

[2]Institut de Ciències de l'Espai (IEEC-CSIC), Can Magrans, S/N, E-08193 Cerdanyola del Vallès, Catalonia, Spain
and

[3]Submillimeter Array, Academia Sinica Institute of Astronomy and Astrophysics, 645 N. Aohoku Place, Hilo, HI 96720, USA

This would go great at the start of the Intro.

Abstract

Understanding the role of magnetic fields in star-forming regions allows us to test ideas about free-fall collapse and support mechanisms in molecular clouds, filling in details about the star formation process. ~~Magnetic fields are commonly probed through linear polarization observations from dust continuum and/or molecular spectral transitions, and analysed through the Davis-Chandrasekhar-Fermi method.~~ For molecular lines circular polarization is usually ignored, largely because of difficulty in measurement and its assumed irrelevance. We ~~find in~~ searched archival data of the Submillimeter Array (SMA[a]) ~~several examples~~ to find evidence of circular polarization in common molecular tracers, most notably CO. This circular polarization possibly arises from anisotropic resonant scattering implying that some background linearly polarized flux is being converted to circular polarization. We find circular polarization in NGC7538, IRC+10216 and Orion KL ~~to sufficient degrees that we believe~~ for transitions of ^{12}CO, ..., to levels high enough to suggest that the presence of circular polarization in these spectral lines is widespread for such objects. This implies ~~implying~~ that an important piece of information has been missed when studying magnetic fields through linear polarization from molecular spectral lines in the interstellar medium.

This goes at the end of the Intro

1. INTRODUCTION

~~This section will cover the background of measuring magnetic fields in the interstellar medium (ISM) and~~ In Section 2 ~~will~~ we discuss the issues that arise when doing polarimetry with radio interferometry, focusing specifically on circular polarization (CP). Section 4 presents archival observations of four objects made with the Submillimeter Array (SMA) on Mauna Kea and makes the case that these circular polarization detections are real and physical. Section 3 will give in detail our scheme for correcting a spurious source of CP that arises with the SMA. Finally in Section 5 we will highlight the significance of these CP detections and summarize relevant research.

Since we can only measure the radiation from star-forming regions, astronomers use polarimetry to infer ~~properties like the direction and magnitude~~ the magnitude's orientation of the magnetic field. The Davis-Chandrasekhar-Fermi (DCF) (Chandrasekhar & Fermi 1953) is one method that uses the dispersion of polarization angles (PA) of linear polarization (LP) ~~to find the magnitude and direction~~ for such studies using corresponding maps of the plane-of-the-sky component of the magnetic field. The presence of a magnetic field leads to linearly polarized radiation because dust and molecules will align themselves relative to the field. ~~The~~ Aligned particles can emit radiation ~~that is~~ with a net level of linearly polarized ation greater than zero. Aligned dust ~~will~~ can also absorb radiation whose polarization is aligned with its long axis, acting as a dust sort of polarizing grid. Thus measuring the amount of linear polarization in the infrared continuum tells us about the degree to which the dust is aligned with the magnetic field, which in turn ~~tells~~ can tell us about the strength of the magnetic field (Chandrasekhar & Fermi 1953; Crutcher 2012).

The alignment of molecules and their interaction with the ambient magnetic field can cause that molecule's transitions to be linearly polarized by a few percent through the so-called Goldreich-Kylafis effect (Goldreich & Kylafis 1981). As with dust, the PA associated with the linear polarization in the spectral line can be measured and used to infer properties of the magnetic field through a dispersion analysis (Chandrasekhar & Fermi 1953; Crutcher 2012).

However, ~~A~~ a significant amount of unexpected circular polariza-

[a] The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

define "Im{ }"

tion was reported by Houde et al. (2013) in a rotational transition of CO using the Caltech Submillimeter Observatory (CSO), a common tracer of ~~the~~ magnetic fields through LP (Crutcher 2012). The presence of circular polarization in a molecular transition can be explained with Zeeman splitting for some molecules/transitions possessing a significant magnetic momeny (e.g., CN), but CO is highly insensitive to the Zeeman effect. In addition, the observed Stokes V profile in Orion KL was positive and symmetric, which is also unexpected since Zeeman splitting usually gives rise to an approximately antisymmetric Stokes V profile. To explain this detection a model was proposed whereby linearly polarized light is converted to circularly polarized light through anisotropic resonant scattering (ARS) (Houde et al. 2013; Houde 2014). This was further tested in the supernova remnant IC443 by Hezareh et al. (2013), where the measured ~~circularly polarized~~ CP flux of CO lines ($J = 2 \to 1$) and ($J = 1 \to 0$) were ~~'re-added'~~ 'reinserted' into the measured ~~linearly polarized~~ LP flux to ~~correct the polarization angles~~ account for the LP-to-CP conversion & its effect on the PA. They found that the ~~polarization angles~~ PA obtained from the CO ~~tracers~~ different transitions only agreed with each other & with those obtained from dust polarimetry after the ~~circularly polarized~~ CP flux was accounted for. If ARS is common to other objects then using ~~linear polarization~~ LP in CO as a tracer of the magnetic field will ~~have~~ introduce a systematic error unless the ~~circular polarization~~ CP of CO~~'s~~ lines are also measured. The goal of this paper is to show several examples of such circular polarization.

2. MEASUREMENT OF CP WITH RADIO INTERFEROMETRY

The measurement of circular polarization is challenging to calibrate, especially when using radio interferometers like the SMA or ALMA. The SMA polarimeter uses a quarter-waveplate (QWP) to usually convert incident ~~linearly polarized~~ LP light to ~~circularly polarized~~ CP light ~~primarily~~ to measure ~~linear polarization~~ LP signals. While not its ~~intended~~ most common use, at the SMA, the QWP can work the other way to measure CP: incident CP is converted to LP and then measured by the receivers. ALMA on the other hand uses linear feeds and measures the linearly polarized light directly. While both types of feeds can be used to measure ~~circular polarization~~ CP, the calibration process is different Sault et al. (1996). ~~Currently~~ While ALMA does not yet support measuring Stokes V reliably, the SMA has been used to take precise measurements of CP in Sgr A* ~~as reported in~~ (Muñoz et al. (2012). For a discussion on measuring CP with radio interferometry and on design choices at the SMA (such as the choice of converting from linear- to circular-polarization and vice-versa) see Hamaker et al. (1996); Marrone et al. (2008).

2.1. *Linear vs. Circular Feeds*

To illustrate briefly the differences between the two feed types consider the following: with orthogonal circular polarization bases, the Stokes V parameter for a beam of light is defined by $V = \langle E_L^2\rangle - \langle E_R^2\rangle$, where ~~$E$ is~~ E_L & E_R are the electric fields ~~vector and L and R correspond to the orthogonal~~ left-CP and right-CP ~~bases~~ respectively. With orthogonal linear bases Stokes V is defined by $V = -2\mathrm{Im}(E_xE_y^*)$ where E_x and E_y are the ~~linear bases~~ LP fields. In the ~~circular~~ CP case we take the difference of two measured intensities while the linear feed case requires us to measure the phase of the electromagnetic wave.

Now, when the measurement is made with interferometry it is the visibilities (the correlated waveforms between a pair of antennae) that are measured. In the circular case the Stokes V visibility ~~is roughly~~ scales as $\mathcal{V}_V \propto \mathcal{V}_{RR} - \mathcal{V}_{LL}$, where $\mathcal{V}_{RR}$ and $\mathcal{V}_{LL}$ are the visibilities obtained from correlating two antenna measuring right-CP and left-CP, respectively. In the linear feed case the Stokes V visibility is coupled with the Stokes Q and U visibilities (see Section 4.1 of Thompson et al. 2001). This means the Stokes Q and U of any calibration object must be measured as well. This is not possible with the SMA setup used for the observations presented in this paper.

spaces

3. SQUINT CORRECTION

Here we describe spurious Stokes V that arises when using the SMA and our scheme for correcting it. This instrumental Stokes V comes from a slight pointing offset between the left- and right-handed CP beams.

The archival data used was in all cases observed with the goal of measuring linear polarization (i.e., the Stokes Q and Stokes U parameters). On the SMA this is done with a quarter-waveplate placed in front of the linear receivers to convert incident circular polarization (CP) to linear polarization. While this method suffers from the errors that arise when subtracting two large measurements from each other, it avoids having to solve for the linear polarization terms of calibration objects when obtaining Stokes V (Marrone et al. 2008; Thompson et al. 2001). Obtaining Stokes V from the visibilities measured with circular feeds is done as follows. Given antennae a and b, the Stokes V visibility in the circular feed case is found through (Muñoz et al. 2012):

$$\mathcal{V}_V \simeq \frac{1}{2}\Big\{\mathcal{V}_{RR}/(g_{Ra}g^*_{Rb}) - \mathcal{V}_{LL}/(g_{La}g^*_{Lb})\Big\}, \qquad (1)$$

where the right-handed CP and left-handed CP visibilities are $\mathcal{V}_{RR}$ and $\mathcal{V}_{LL}$ and are measured by orienting the quarter-waveplate that is placed in the beam of the antennae and correlating the responses of the antennae (Marrone et al. 2008). The complex gain factors for each polarization for each antennae are g_{Ra}, g_{Rb}, g_{La} and g_{Lb} with 'R' and 'L' for right- and left-CP, respectively. Because the Stokes V visibility is found by taking the dif-

The main goal of this paper is to find further evidence of CP in more objects & molecular lines through a search of archival data of the SMA. In Section 2 ---