# Non-Zeeman Circular Polarization of Molecular Spectral Lines Present in Several Star-Forming Regions

M. A. Chamma[1] and M. Houde[1]

[1] *Department of Physics and Astronomy, The University of Western Ontario, London, ON, N6A 3K7, Canada*

Understanding the magnetic field in star-forming regions allows us to test ideas about free-fall collapse and support mechanisms in molecular clouds. These magnetic fields are usually probed through linear polarization observations of molecular spectral transitions and analysed by the Goldreich-Kylafis effect and Davis-Chandrasekhar-Fermi method, but circular polarization of these lines is usually ignored, largely because of its difficulty in measuring and because of its assumed irrelevance. We find in archival data of the Submillimeter Array several examples of circular polarization in common molecular tracers, most notably CO. This circular polarization possibly arises from anisotropic resonant scattering implying that some of the linearly polarized flux is being converted and lost to so far unmeasured circular polarization flux. We find circular polarization in NGC7538, IRC+10216, Orion KL to sufficient degrees that we believe the presence of circular polarization in these spectral lines is common to all such objects, implying an important piece of information has been missed when measuring the $\boldsymbol{B}$ field and its direction in star-forming regions.

## Observations

We collected radio interferometric archival observations from the Submillimeter Array archive that had been measured using the circular feeds, a similar setup to that used by [1] to measure circular polarization in Sgr A*. Because the archival observations were not taken with measurements of circular polarization in mind the SNR is often very low, and we average velocity channels to increase the SNR at the cost of resolution. This works because white noise will average out leaving larger peaks.

The four objects we present here are Orion KL, NGC7538, NGC1333 and IRC+10216. All are star-forming regions with the exception of IRC+10216 which is a carbon star. The visibility data is corrected for squint, an instrumental artifact that gives rise to spurious Stokes V. Squint gives rise to distinct pairs of positive and negative peaks of Stokes V. Maps are then made of the continuum and lines for each object. The squint correction is confirmed visually by inspecting the Stokes V maps, where we see the pairs of peaks largely disappear.

| Object | Coordinates (J2000) | Array Configuration | Date Observed |
|---|---|---|---|
| **IRC+10216** | RA $09^h47^m57.381^s$ Dec +13°16'43.70" | Compact | 2009-11-24 |
| **NGC7538** | RA $23^h13^m44.771^s$ Dec +61°26'48.85" | Compact | 2014-10-28 |
| **Orion KL** | RA $05^h35^m14.501^s$ Dec -05°22'30.40" | Compact | 2008-01-06 |
| **NGC1333** | RA $03^h28^m55.580^s$ Dec +31°14'37.10" | Compact | 2010-10-14 |

Table I: Summary of Archival Observations Used

Figure ?? shows Stokes I and Stokes V spectra obtained from the maps and taken through the peak of Stokes V. Both corrected and uncorrected spectra are shown. Notice in most cases the Stokes V signal decreases after squint correction except for the case of CO in NGC7538, while in many other lines the Stokes V signal disappears completely. Stokes V can be found in the average of all the visibility data, though the significance is 3-5$\sigma$ in that case compared to a significance of around 6-10$\sigma$ when the spectra is taken from the inverted maps.

In the case of Orion KL the lines of CO (345.8GHz) and SiO (347.2GHz) have similar intensities but the CO line has a strong Stokes V signal while the SiO has very little. This reassures us that the measurement of Stokes I is not leaking into Stokes V.

Table I shows a summary of the objects presented and related information.

## 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 (Stokes Q and Stokes U). On the SMA this is done with a quarter-waveplate placed infront of the linear receivers to convert incident linear polarization to circular polarization (CP). This is done because the measurement with interferometry is more easily made with circularly-polarized feeds [2, 3]. While it is preferred to use linear feeds for measuing circular polarization (Stokes V) it is possible to get Stokes V from the visibilities measured with circular feeds. Given antennae $a$ and $b$, the Stokes V visibility in the circular feed case is found through[1]:

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

Here 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. The complex gain factors for each polarization for each antennae are $g_{Ra}$, $g_{Rb}$, $g_{La}$ and $g_{Lb}$. Because the Stokes V visibility is found by taking the difference of two beams a slight offset gives rise to pairs of positive and negative peaks of Stokes V, as shown in Figure ??. This offset likely arises because of slight differences in the index of refraction of the quarter-waveplate when it is rotated.

Because the visibilities are the Fourier transform of the intensity image, an offset in image space is a complex coefficient in visibility space that can be absorbed into the complex gain coefficients (see Appendix). Thus it is easiest to correct for the offset in image-space by using *Miriad* to solve for the gain coefficients on each beam. Specifically the process is:

1. Observations are calibrated for gain and phase in the usual way using calibration observations of 'good' sources (usually quasars like 3C84, 3C454, etc.) (See Miriad User Guide[4])

2. Visibilities are split into line-free continuum data and just line data. These are then mapped and used to obtain CLEAN models

3. The split continuum and line data are split further into $LL$ and $RR$ visibilities. *Miriad*'s `selfcal` is used on the continuum data to solve for the gain coefficients of each antenna and each polarization (L or R). This is done by minimizing the difference between measured visibilities $\mathcal{V}_{ij}$ of antennae $i$ and $j$ and model visibilities $\hat{\mathcal{V}}_{ij}$ according to $\epsilon^2 = \sum |\mathcal{V}_{ij} - g_i g_j^* \hat{\mathcal{V}}_{ij}|^2$ for each of the correlations $LL$ and $RR$ [4, 5]. The model visibilities used are those found earlier.

4. The gains found from the continuum $LL$ data is then applied to the line $LL$ data. The gains found from the continuum RR data is applied to the line RR data.

5. The different polarizations ($LL$, $RR$, $RL$, $LR$) are recombined and inverted to produce corrected maps. Spectra can be obtained either from the corrected visibilities or the maps.

Figure ?? shows maps before and after this correction is applied.

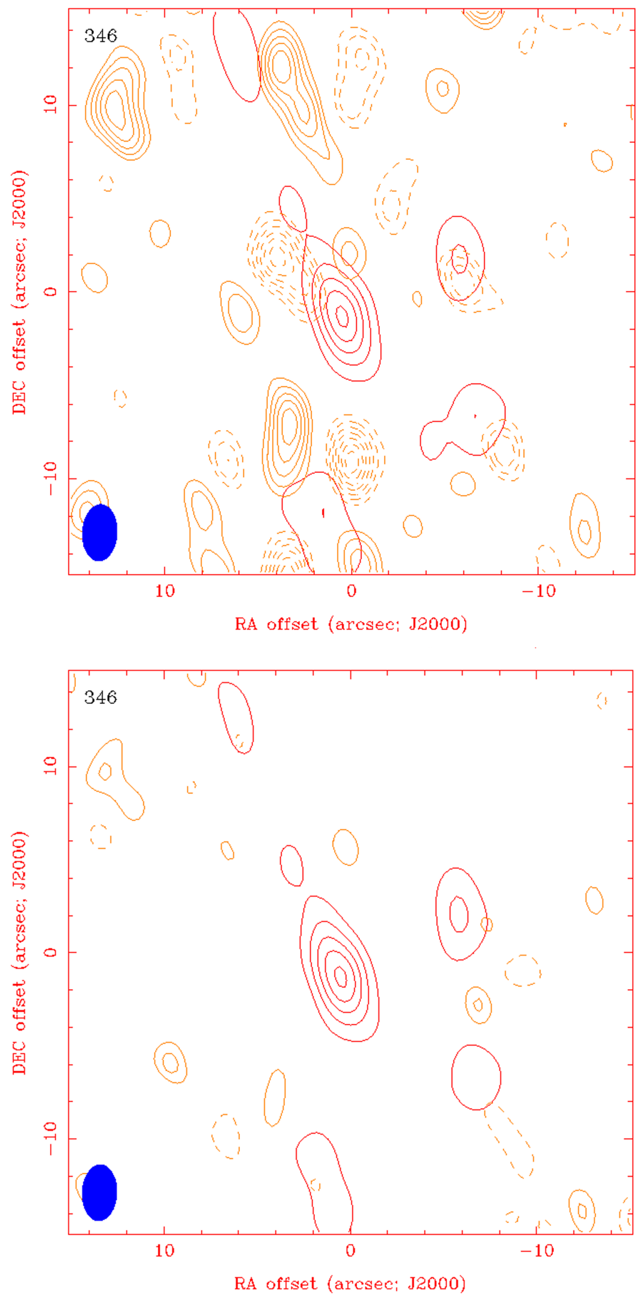


Figure 1: (placeholder) Map of the continuum around 345GHz in Orion KL before (top) and after (bottom) squint correction. Red contours are Stokes I, orange (green?) contours are Stokes V. Dashed lines denote negative values, solid lines denote positive values. Note the multiple pairs of positive and negative Stokes V peaks. These largely disappear after correction. The contour scales on both maps are identical. Red Stokes I contours are at 15%, 35%, 55%, 75% and 95% of the peak intensity. Orange (green?) Stokes V contours are at -8, -7, -6, -5, -4, -3, -2, 2, 3, 4, 5, 6, 7 and 8$\sigma$ levels.


[1] Munoz et al. 2012

[2] Marrone et al. 2008

[3] Sault et al. 1996

[4] Sault, B., Killeen, N.: 2008, *Miriad* Users Guide, Australia Telescope National Facility

[5] Schwab 1980