

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

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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~~ ^{through} molecular spectral transitions and analysed by the Goldreich-Kylafis effect and Davis-Chandrasekhar-Fermi method. ~~but~~ ^{For molecular lines} circular polarization ~~of these lines~~ is usually ignored, largely because of ~~its~~ ^{measurement} 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~~ ^{background} 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~~ ^{widespread for} such objects, implying an important piece of information has been missed when ~~measuring the B field and its direction~~ ^{that} in star-forming regions.

Observations

We collected radio interferometric archival observations from the Submillimeter Array ^(SMA) 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 ^{had to} average velocity channels to increase the SNR at the cost of resolution. ^{spectral} This works ~~because white noise will average out leaving larger peaks.~~ ^{→ Maybe you should state the typical SNR you get that way.}

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 ^{are} 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. ^{where?} 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. ^{More details on squint correction will be given in the next section.}

The first three are well-known star-formation regions, while IRC+10216 is an evolved carbon star.

Object	Coordinates (J2000)	Array Configuration	Date Observed
IRC+10216	RA 09 ^h 47 ^m 57.381 ^s Dec +13°16'43.70"	Compact	2009-11-24
NGC7538	RA 23 ^h 13 ^m 44.771 ^s Dec +61°26'48.85"	Compact	2014-10-28
Orion KL	RA 05 ^h 35 ^m 14.501 ^s Dec -05°22'30.40"	Compact	2008-01-06
NGC1333	RA 03 ^h 28 ^m 55.580 ^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~~ ^{at} 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 ^{for} 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 σ in that case compared to ^{approximately} ~~a significance of around~~ 6-10 σ when the spectra is taken from the inverted maps. ^{as well,}

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. ^{significantly}

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

^{, which are sensitive to two orthogonal polarization states,}

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). ^{parameters} On the SMA this is done with a quarter-waveplate placed ^{in front of the} ~~linear~~ receivers to convert incident ~~linear~~ ^{circular (CP)} polarization to ~~circular~~ ^{linear} 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 measuring ~~circular~~ ^{CP} 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]:

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

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

with 'R' & 'L' for right & left-CP, respectively.

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. \rightarrow reference?

(for the intensity map). equivalent

Because the visibilities are the Fourier transform of the intensity image, an offset in image space is ~~a complex~~ \rightarrow to a complex exponential term 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: \rightarrow citation

good

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~~ ^{separate} 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.~~ ^{similarly for the *RR* continuum & line 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.

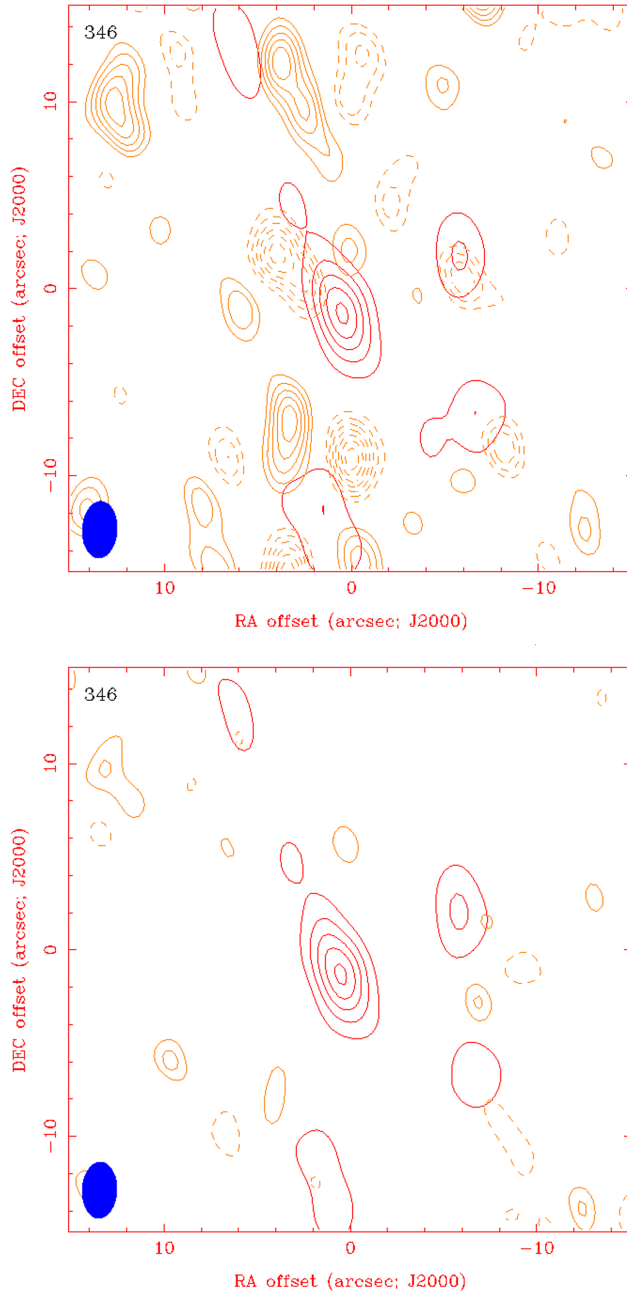


Figure 1: (placeholder) Map of the continuum around 345GHz in Orion KL before (top) and after (bottom) squint correction. Red contours are Stokes I, orange (green?) contours are Stokes V. Dashed lines denote negative values, solid lines denote positive values. Note the multiple pairs of positive and 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 8σ levels.

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- [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