Mapping Large-scale Magnetic Fields in Giant Molecular Clouds

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1 The SPARO experiment

We report observations of magnetic fields in Giant Molecular Clouds (GMCs), obtained using the technique of submillimeter polarimetry. We used a polarimeter called SPARO [1, 2] that we built at Northwestern U. and that we use together with a 2-meter telescope at South Pole station. In comparison with submillimeter polarimeters that have been operated from larger telescopes on Mauna Kea, SPARO obtains relatively coarse angular resolution but much better sensitivity to fainter, more extended emission. We have also discussed these recent SPARO observations in a paper in the Astrophysical Journal [3].

2 Are B-fields in GMCs correlated with Galactic B-fields?

The question that we address here is whether magnetic field directions in GMCs are correlated with the direction of the large-scale magnetic field of the Galaxy. Another way to ask this question is to consider the unknown physical process that causes a large volume of diffuse interstellar matter to come together and form a GMC, and to ask whether this process preserves the memory of the original magnetic field direction, or whether instead the field gets scrambled. The question has been addressed via observations of OH masers in molecular clouds [4, 5, 6] with some investigators finding evidence for a correlation.

The question can also be addressed using submillimeter polarimetry. A collection of measured field directions that were mostly obtained using a polarimeter operated at the Caltech Submillimeter Observatory on Mauna Kea has been studied [7] in order to determine if the field directions are correlated with the direction of the Galactic plane. No correlation was found. The

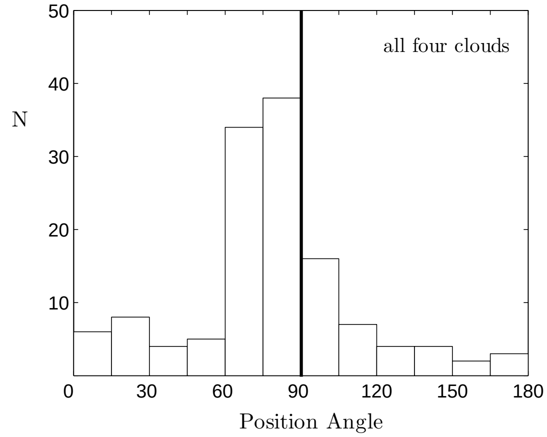

Fig. 1. Histogram of the 131 magnetic field directions measured by SPARO in the four GMCs [3]. The horizontal axis gives the field angle in Galactic coordinates, measured from Galactic North. Ninety degrees corresponds to magnetic fields parallel to the Galactic plane.

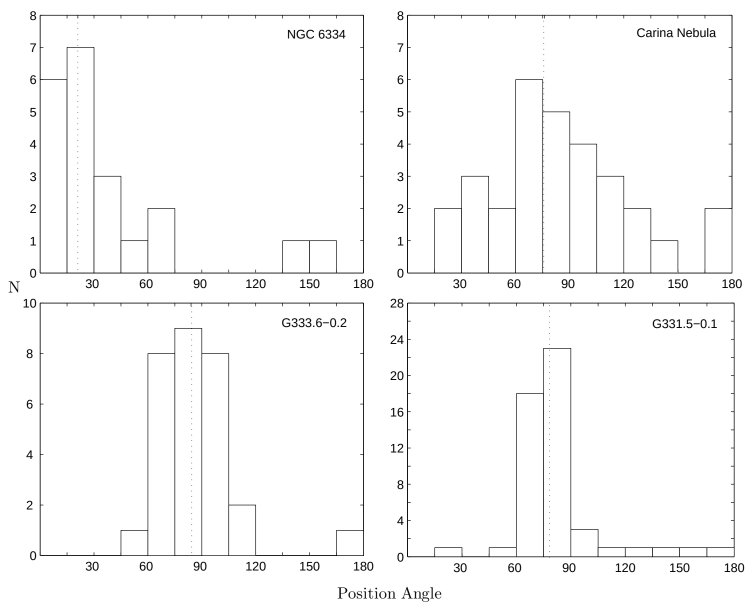

Fig. 2. Same as Figure 1, but broken up into four histograms, one for each GMC. The vertical dotted lines show the mean magnetic field direction for each cloud [3].

SPARO data set consists of magnetic field maps for four GMCs in the Galactic disk, at distances ranging from about two to about five kpc [3]. For each of the four clouds, we measured polarization along a few dozen sight lines, and we obtained a total of 131 measurements. Figure 1 shows a histogram of the 131 measured field directions. The dark vertical line in the middle of the histogram corresponds to having magnetic fields parallel to the Galactic plane. We see that the fields are preferentially parallel to the Galactic plane and thus also preferentially parallel to the large scale field of the Galaxy. The earlier submillimeter study [7] did not see this because it was based on small scale maps of fields near flux peaks in GMCs, whereas our maps cover much more sky area [3] and thus truly sample the global magnetic fields of GMCs.

Figure 2 shows another way to look at the data, with four individual histograms, one for each GMC. Each cloud has a well defined peak in the distribution of field angles, and in three cases the mean field angle is within 15 degrees of the plane. One cloud, NGC 6334, has its field rotated away from the plane by a large angle. This cloud presents a bit of a puzzle, but note that the distribution of mean field angles for the four clouds is not consistent with a random distribution. If one were to chose mean field angles at random, then the probability for finding three out of the four angles to be within 15 degrees of the plane would be less than 2% [3]. Thus, our data show a statistically significant correlation of GMC fields with Galactic plane orientation.

3 Using optical polarimetry to probe the Galactic field

Note that even if GMC formation does preserve mean field direction, we should not expect to see all GMCs having fields exactly parallel to the Galactic plane, because the Galactic field itself has large scale fluctuations. If NGC 6334 were to have formed in a region of the Galaxy where, due to these fluctuations, the Galactic field was rotated away from the plane by a large angle, then the cloud would end up with its field rotated away from the plane, as we observe. In principle, we can check this hypothesis by using optical polarimetry to sample the Galactic field in the vicinity of each of our four GMCs. Before doing this we need to decide how big a volume of space around each GMC we should sample. A natural size to use is a cube 400 pc on a side, corresponding to a volume of diffuse ISM that contains enough mass to form a GMC [8].

We have carried out a study based on the stellar polarimetry database assembled by Carl Heiles [9]. First we examined how the selective extinction for these stars depends on distance. We found [3] that the extinction vs. distance curve rises linearly at first, as expected for stars chosen at random, but then it flattens. This flattening suggests that the Heiles database contains a selection effect whereby a star at a great distance (say, 3 kpc) has a better chance of making it into the database if the sight-line toward that star is relatively dust-free. Because of this possibility for bias, we decided to avoid using data from the flat part of the curve. The closest of the four GMCs mapped by SPARO is NGC 6334, the discrepant cloud, at 1.7 kpc. The other three are at distances well into the flat part of the extinction vs. distance curve, so we have not attempted to study the Galactic fields for these three. But we did carry out a study of the field in the region surrounding NGC 6334, as well as in other nearby regions for comparison purposes [3].

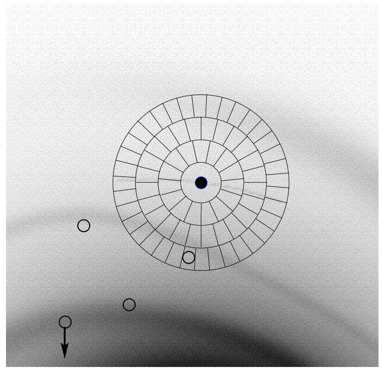

Fig. 3. "Cells" used to analyze optical polarimetry data. View is looking down on the Galaxy's disk from Galactic North. A filled circle indicates the Sun's location, with the Galactic center well off the bottom of the image. Approximate locations of spiral arms are shown using a gray scale image from a model [10]. Open circles show locations of SPARO GMCs. (One is slightly off the bottom of the image, as indicated). The local region of the Galaxy is divided up using three rings of three-dimensional cells [3], shown here in projection.

As shown in Figure 3, we divided the nearby regions of the Galaxy into "cells", one of which is centered on the NGC 6334 cloud, with the goal of using the optical polarimetry data to estimate the mean field direction for each cell. The cell dimensions (300 by 120 by 500 pc) deviate somewhat from the ideal of 400 pc for practical reasons [3]. To estimate the field angle for any given cell, we used "background stars", chosen to be near the back face of the cell, and "foreground stars", chosen to be near the front face. We then estimated the portion of the polarization of a given background star that is due specifically to dust in the cell, by taking differences between Stokes parameters of that background star and the Stokes parameters of a selection of foreground stars chosen to be near in the sky to the background star [3].

The stars in the database are not evenly distributed in the sky, and many of our cells have very few or no stars. We implemented cuts designed to eliminate cells with too few stars, or with too much disorder in the derived magnetic field directions [3]. Only 11 cells survived these cuts (the NGC 6334 cell is one of them) and the histogram at the upper left of Figure 4 shows the distribution of mean field angles. Even though we excluded the most distant stars, the background stars for the third ring of cells (Fig. 3) are still sufficiently

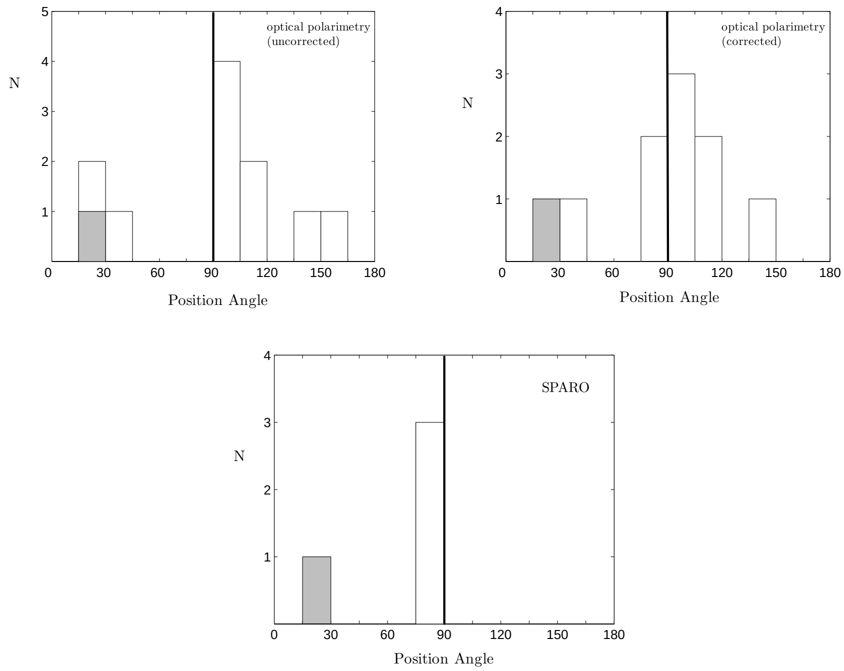

Fig. 4. Histograms from optical polarimetry analysis (upper left and right) and SPARO data (bottom). For all three histograms, the horizontal axis shows the field angle, and the direction corresponding to the Galactic plane is indicated with a dark vertical line. At upper left we show the distribution of mean field angles for 11 optical polarimetry cells, and to the right of this we show the result when the analysis is repeated with bias correction applied (see discussion in text). The bottom plot shows the distribution of the four mean field angles determined by SPARO for the four GMCs we observed. In all three histograms, the box corresponding to NGC 6334 is shaded.

far to put them in the part of the extinction vs. distance curve where the above-mentioned flattening is starting to become evident. We were concerned about the effects of the above-mentioned bias, and as a way to gage this we devised a crude way to correct for the bias [3]. First we made a rough estimate for how badly the extinction is being underestimated at any given distance, based on the observed flattening of the extinction vs. distance curve. Then, under the assumption that the Stokes parameters are being underestimated by the same factor, we corrected them upward. Finally we repeated our entire analysis using these corrected Stokes parameters, and the result is shown in the upper right of Figure 4. Despite the differences, the two optical polarimetry histograms (upper left and upper right of Fig. 4) both show an apparent peak corresponding to cells having mean field parallel to the plane, and both also show significant disorder.

Next we compare our optical polarimetry results to the SPARO results for the mean fields of the four GMCs, shown in the bottom histogram of Figure 4. Recall (Sect. 2) that three of the GMCs have their mean fields well aligned with the Galactic plane, while NGC 6334 is an outlier. In the bottom histogram of Figure 4, the NGC 6334 cloud is shaded. In the upper histograms of Figure 4, the cell corresponding to NGC 6334 is shaded. We see from the position of the shaded box in these upper histograms that the region where NGC 6334 formed has a projected field direction that is unusual in that it is rotated far away from the Galactic plane. In terms of agreement of cell field direction with Galactic plane, it is the worst of 10 cells (upper right histogram) or one of the worst 3 of 11 (upper left histogram). The fact that the NGC 6334 cell is unusual may explain why the NGC 6334 cloud is unusual. The results of our optical polarimetry study are thus consistent with the idea that GMC formation preserves the memory of the large-scale field (measured on ~ 400 pc scales).

This result and the statistically significant correlation we see between GMC fields and the Galactic plane (Sect. 2) can both be naturally understood if the GMC formation process does indeed preserve the mean field direction. This work was supported by a grant to Northwestern U. from the NSF's Office of Polar Programs.

References

1. G. Novak, D. T. Chuss, T. Renbarger, G. S. Griffin, M. G. Newcomb, J. B. Peterson, R. F. Loewenstein, D. Pernic, and J. L. Dotson: Ap. J. Lett. **583**, L83 (2003)
2. T. Renbarger, D. T. Chuss, J. L. Dotson, G. S. Griffin, J. L. Hanna, R. F. Loewenstein, P. S. Malhotra, J. L. Marshall, G. Novak, and R. J. Pernic: P.A.S.P **116**, 415 (2004)
3. H. Li, G. S. Griffin, M. Krejny, G. Novak, R. F. Loewenstein, M. G. Newcomb, P. G. Calisse, and D. T. Chuss: Ap. J. **648**, 340 (2006)
4. M. J. Reid and E. M. Silverstein: Ap. J. **361**, 483 (1990)
5. A. Baudry, J. F. Desmurs, T. L. Wilson, and R. J. Cohen: A. & A. **325**, 255 (1997)
6. V. L. Fish, M. J. Reid, A. L. Argon, and K. M. Menten: Ap. J. **596**, 328 (2003)
7. R. H. Hildebrand: In *Astrophysical Spectropolarimetry*, edited by J. Trujillo-Bueno, F. Moreno-Insertis, & F. Sanchez (Cambridge University Press, Cambridge, 2002) p 265
8. J. P. Williams, L. Blitz, and C. F. McKee: In *Protostars and Planets IV*, edited by V. Mannings, A. P. Boss, & S. S. Russel (University of Arizona Press, Tucson, 2000), p 97
9. C. Heiles: Astron. J. **119**, 923 (2000)
10. R. Drimmel and D. N. Spergel: Ap. J. **556**, 181 (2001)