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Observation of Toroidal Magnetic Fields on 100 pc Scales in the Galactic Center

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Abstract. We present new submillimeter polarimetric observations of the Galactic center region, made using the SPARO polarimeter that operates at the South Pole. Compared with previous submillimeter polarimetry of this region, our measurements cover much more sky area, and they imply that the molecular gas in the central few hundred pc is threaded by a large scale toroidal magnetic field. We consider this result together with radio observations that show evidence for poloidal fields in the Galactic center, and with Faraday rotation observations. We compare all of these observations with a magnetodynamic model for the Galactic center.

1 Introduction

Our contribution to the Galactic Center Workshop 2002 was to present new submillimeter polarimetric observations of the Galactic center, obtained using the SPARO instrument at South Pole station. SPARO (the Submillimeter Polarimeter for Antarctic Remote Observations), is a 9-pixel submillimeter array polarimeter incorporating ^{3}He-cooled detectors (Renbarger et al. 2003). It is operated on the Viper telescope (Peterson et al. 2000).

Submillimeter thermal emission from interstellar dust grains is generally polarized, due to magnetic alignment of grains. Thus, submillimeter polarimetry provides a method for mapping interstellar magnetic fields. The SPARO map extends over a much larger sky area than has been covered in previous submillimeter polarimetric maps, so it provides new information on the large-scale configuration of the magnetic field in the Galactic center. This can be compared with the results of radio synchrotron observations and Faraday rotation observations, both of which also give information about magnetic fields. We have already published a paper that presents our SPARO results, and compares them with synchrotron and Faraday observations (Novak et al. 2003). Accordingly, here we will merely summarize the Novak et al. (2003) paper.

2 SPARO results

As is typical for submillimeter continuum observations, measurements made using SPARO are not absolute, but rather are differential. Specifically, the flux that SPARO measures is the difference between the

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flux at the main observing position and the average flux for the two sky reference positions, which are separated from the main position by +0.5° and −0.5° in cross-elevation, respectively. We observed the Galactic center for a total of five weeks during the interval April–July 2000. The results are presented in Figure 1. The contours correspond to a 450 μm photometric map made using SPARO, and they clearly show the large concentration of molecular gas that is associated with the innermost few hundred pc of the Galaxy. The highest column density occurs at the position of Sgr B2, displaced from the center of the Galaxy toward positive Galactic longitudes. The SPARO polarization results are shown using bar symbols. The orientation of each bar gives the inferred magnetic field direction, that is orthogonal to the E-vector of the measured polarization, and the length of the bar is proportional to the degree of polarization.

The SPARO polarization results imply that the magnetic field permeating the Galactic center molecular gas, when projected onto the plane of the sky, is for the most part parallel to the Galactic plane. The most natural way to account for this is to suppose that the molecular gas in the Galactic center is threaded by a large scale magnetic field having a toroidal configuration. This had already been suggested, based on earlier polarimetry results at far-infrared/submillimeter wavelengths (Morris et al. 1992, Novak et al. 2000). However, the SPARO results cover much more sky area than the previous observations, and thus they provide the strongest evidence yet obtained for the existence of this toroidal large-scale field.

Figure 2 shows the SPARO magnetic "vectors" superposed on a radio continuum image (gray scale) showing Galactic center non-thermal radio filaments. These filaments trace magnetic fields running preferentially perpendicular to the Galactic plane. They appear to delineate a large scale magnetic field with a poloidal configuration. It is clear from Figure 2 that the magnetic field in the central few hundred pc is neither purely toroidal, nor purely poloidal. Rather, there appear to be regions in which toroidal fields dominate as well as regions in which poloidal fields dominate. In particular, the field seems to be toroidal in the denser molecular material that is concentrated near the Galactic plane, and poloidal in the more diffuse, hotter, and more tenuous synchrotron-emitting regions.

3 The model of Uchida, Shibata, and Sofue

A theoretical model for the Galactic center that may be able account for the separate "poloidal-dominant" and "toroidal-dominant" regions that we see in Figure 2 is the magnetodynamic model developed by Uchida, Shibata & Sofue (1985), and further refined by Shibata & Uchida (1987). This model was developed in order to explain the "Galactic Center Lobe" (GCL), that is a limb-brightened radio structure with a size of several hundred pc extending from the plane of the Galaxy up towards positive Galactic latitudes (Sofue & Handa 1984). In the model of Uchida et al. (1985), the GCL represents a gas outflow that is magnetically driven. The model consists of nonsteady axisymmetric magneto-hydrodynamic simulations in which the field is assumed to be perpendicular to the Galactic plane at high Galactic latitudes, but acquires a toroidal component near the Galactic plane due to differential rotation of the gas to which it is coupled via flux-freezing. The stress of the resultant magnetic twist is what drives the outflow. In Novak et al. (2003), we argue that this model is fundamentally consistent with both the poloidal field seen by radio observers and the toroidal field seen by SPARO, provided that we make allowances for the clumpy distribution of the molecular gas.

4 Faraday rotation

It is possible to probe the line-of-sight component of the magnetic field in any region of the Galactic center that contains thermal gas, provided that this region lies along the line-of-sight to a synchrotron source. This is because polarized radio emission suffers Faraday rotation as it passes through thermal gas. The model of Uchida et al. (1985) makes a specific prediction regarding the line-of-sight component of the magnetic field. To visualize this prediction, imagine dividing the Galactic center region into four quadrants

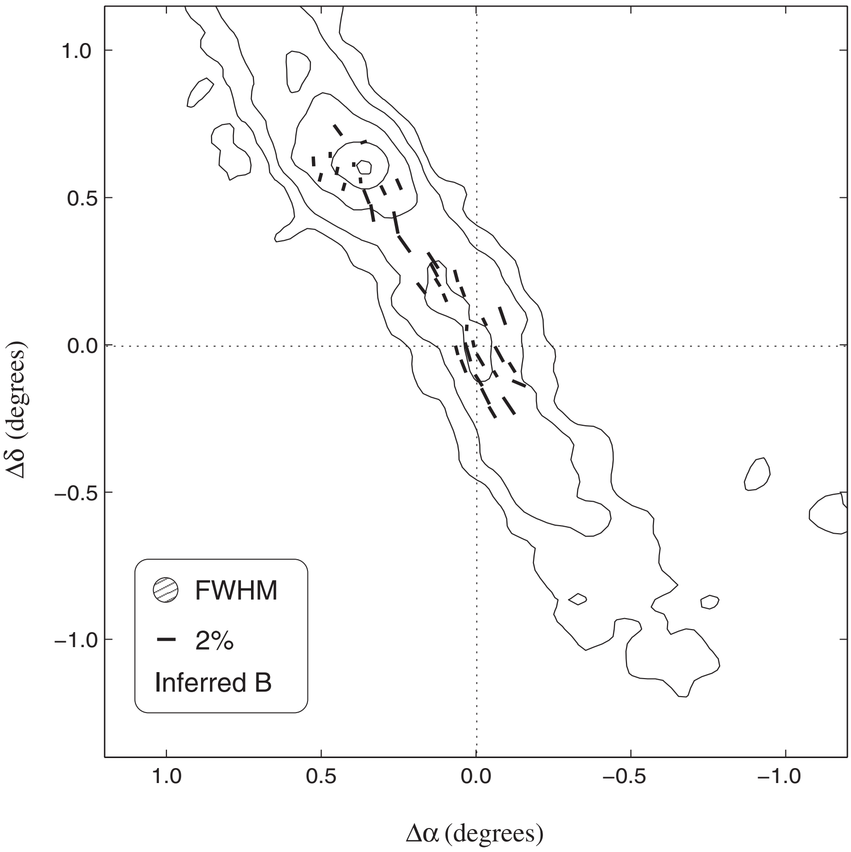

Fig. 1 Results of 450 μm polarimetry (bars) and photometry (contours) of the Galactic center, obtained using SPARO. The distribution of 450 μm flux closely follows the Galactic plane, that lies at a position angle of +31°. Coordinate offsets are measured with respect to the location of Sgr A* (that lies at the intersection of the horizontal and vertical dotted lines). Each bar is drawn parallel to the inferred magnetic field direction (i.e. perpendicular to the E-vector of the measured submillimeter polarization), and the length of the bar indicates the measured degree of polarization (see key at bottom left). Contours are drawn at 0.075, 0.15, 0.30, 0.60, and 0.95 times the peak flux, which is located at the position of Sgr B2. For clarity, negative contours are not shown. The reference beam offsets were the same for polarimetry and photometry and are given in § 2. The 5′ beam of SPARO is shown in the key. Positive Galactic latitudes lie towards the upper right of the figure, and positive Galactic longitudes lie towards upper left.

according to the signs of Galactic longitude and latitude. According to the model, the sign of the line-of-sight field (i.e., towards or away from the observer), should be the same within a quadrant, and opposite in adjacent quadrants.

We carried out a survey of the literature on Faraday rotation measurements toward Galactic center synchrotron sources, and we discovered a pattern of observed reversals in the sign of the Faraday "rotation measure" (hereafter, RM) that matches these predictions. We show this, using plus and minus signs, in Figure 3. The plus sign represents positive RM, and the minus sign represents negative RM. References to the Faraday rotation observations are given in Novak et al. (2003). We note that for RM measurements at positive Galactic longitudes, the asymmetry with respect to the Galactic plane had been noted previously, and Uchida et al. (1985) pointed out the agreement with their model. To our knowledge, Novak et al. (2003)

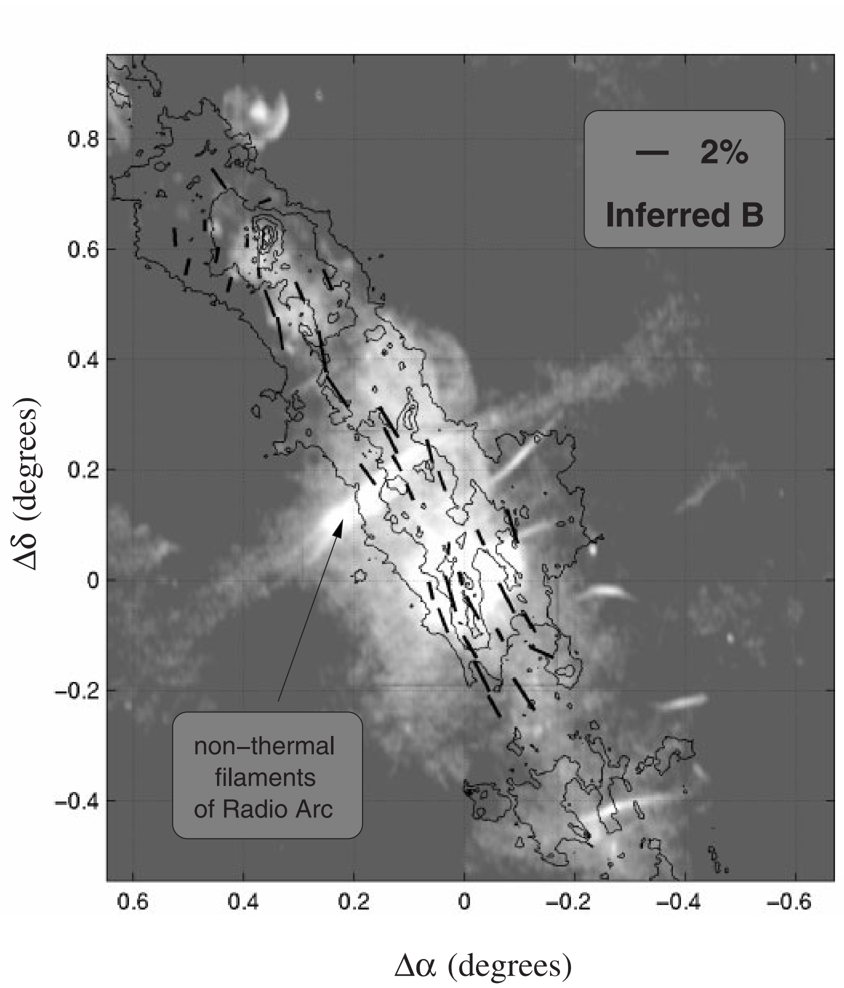

Fig. 2 450 μm polarization measurements (bars) shown together with 90 cm radio continuum image (gray scale, LaRosa et al. 2000), and 850 μm continuum emission (contours, Pierce-Price et al. 2000). As in Fig. 1, the orientation of each bar is parallel to the inferred magnetic field direction (i.e., orthogonal to the measured direction of polarization) and its length is proportional to the degree of polarization. The radio continuum image shows about six locations where non-thermal filaments can be seen. These non-thermal filaments trace magnetic fields in hot ionized regions. The gray scale image is logarithmically scaled, and the contours of 850 μm emission are also logarithmic. Coordinate offsets are measured with respect to the position of Sgr A*. The location of the brightest bundle of non-thermal filaments (referred to as the non-thermal filaments of the Radio Arc) is indicated in the figure.

were the first to compare the signs of the RM measurements that lie towards negative Galactic longitudes with the predictions of the Uchida et al. (1985) model.

The pattern that we see in Figure 3 is the one that results when the poloidal field points toward positive Galactic latitude. If the poloidal field is taken to point in the negative latitude direction, then all of the RM signs should be reversed. Thus, if our interpretation of these data in the context of the Uchida et al. (1985) model is correct, we can conclude that the large scale poloidal field points towards Galactic North.

Considering this pattern of RM reversals together with the SPARO polarization map and the evidence for poloidal fields derived from radio synchrotron maps, we conclude that the available observations do

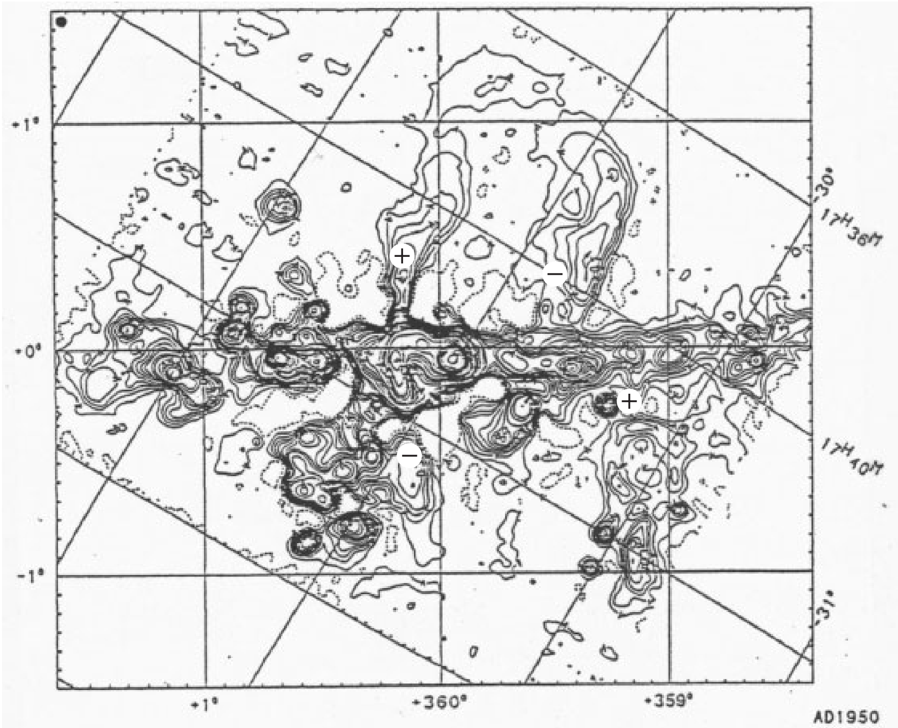

Fig. 3 Contours show distribution of 3.5 cm radio continuum emission from the central 500 pc (Haynes et al. 1992). The plus and minus symbols refer to the sign of the Faraday rotation measure, as discussed in § 4.

support the general picture given by Uchida et al. (1985) for the large-scale magnetic field in the Galactic center. The data, however, are very sparse. More observations, especially of Faraday rotation, are needed.

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