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Results of SPARO 2003: Data Analysis Methods for Submillimeter Polarimetry

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1. Introduction

The submillimeter thermal emission from interstellar dust grains is polarized because the grains are magnetically aligned (Hildebrand, Dragovan, & Novak 1984). Detecting the polarized emission has become one of the principal techniques for studying magnetic field morphology in interstellar clouds.

SPARO (Submillimeter Polarimeter for Antarctic Remote Observations) is an instrument designed to measure 450 μm polarization using the two-meter Viper telescope located at South Pole station. It obtains excellent sensitivity to large-scale polarized submillimeter emission but relatively coarse angular resolution. Initial observations took place in 2000 and mapped the magnetic field of the Galactic center (Novak et al. 2003). The second try came in '03 after an optics upgrade. The '03 targets were Giant Molecular Clouds (GMCs) in the disk of the Galaxy, which are much fainter than the Galactic center. We found that the data analysis method used for the 2000 data (the "standard method") is inadequate for these fainter targets. Accordingly, we developed an improved analysis method that we describe in this paper.

2. The experiment

SPARO uses two nine-pixel arrays of ^{3}He-cooled bolometers (Renbarger et al. 2004). Other key components are the rotating half-wave plate and the free standing wire grid which divides the incident light into two orthogonal polarization components; the transmitted one is called T, and the reflected one is called R. The two components are measured simultaneously by the two bolometer arrays. The Viper telescope is equipped with a flat chopping mirror that has a throw of up to several degrees on the sky. For SPARO '03 observations, we used 0.65° throw and $\sim$3Hz chopping frequency.

The observing steps we use are (Hildebrand et al. 2000) :

(1) Chop between two sky positions, so that the left beam is on the source and the right beam is off the source.

(2) Nod the telescope to another position so that the left beam is off the source while the right beam is on the source (keep chopping).

(3) Repeat (2) (no nod).

(4) Nod the telescope to repeat (1).

The signals from the bolometers are continuously demodulated by the digital signal processor, using a sine wave with frequency and phase synchronized to the chopping mirror. These four steps together are called a ***nod pair***. For each step, there will be 12 demodulated measurements, called ***frames***. Denote the mean of the frames of the ith step by $\overline{frame_i}$, then the total flux can be calculated by $\overline{frame_1}$ - $\overline{frame_2}$ - $\overline{frame_3}$ + $\overline{frame_4}$. To obtain the polarization, we perform one nod pair at each of six half-wave plate positions: 0°, 30°, 60°, 90°, 120°, and 150°. These six nod pairs together are called a ***polarimetic observation***.

3. The standard data analysis method

3.1. The basic idea

The standard method is the method discussed by Hildebrand et al. (2000). For each polarimetic observation, we calculate six values of the ***polarization signal***, S_θ, for each of the nine pixels. The polarization signal is defined as

$$S_\theta = \frac{R_\theta - fT_\theta}{R_\theta + fT_\theta}$$

where R_θ (T_θ) is the flux detected by the R (T) bolometer array when the half-wave plate is at position θ, and f is the relative gain of the two arrays which is calculated from

$$f = \frac{\Sigma R_\theta}{\Sigma T_\theta}$$

There are other ways to calculate f; for example, see Dowell et al. (1998). Then the normalized Stokes parameters q and u can be calculated from the S_θ (Platt et al. 1991; Hildebrand et al. 2000).

3.2. Problems with the standard method

Since the sky noise should not be polarized, it will contribute the same amount to R_θ and fT_θ. So the values of R_θ-fT_θ (D_θ, hereinafter) are almost entirely free of sky noise. On the other hand, the values of R_θ+fT_θ (I_θ hereinafter) can be strongly affected by sky noise and can not be measured as accurately as D_θ for the same integration time. This will not only cause bigger errors in S_θ, but also bias the measured degrees of polarization.

Suppose that I_θ is distributed as a Gaussian function, G, with mean μ and variance σ^2. The bias can be estimated from the expectation value of $\mu/I_\theta = \int_{-\infty}^{0-} + \int_{0+}^{\infty} \frac{\mu}{I_\theta} G dI_\theta$, which varies with the value of σ/μ (Fig.1). Also shown in Fig.1 is another bias function that was estimated by a numerical simulation. The simulation used the standard method to analyze artificial 2% polarized signals where S_θ are divided by numbers randomly chosen from a Gaussian distribution with unity mean. The two estimates are very close; both show that there is a big bias when $\sigma/\mu \geq 1.5$, which is the case for SPARO '03 data (Fig.2).

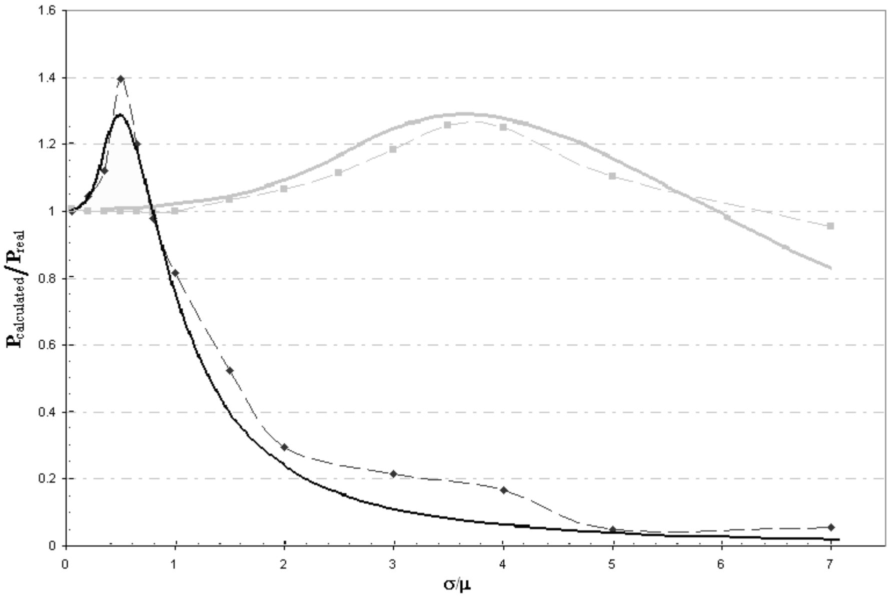

Figure 1. The bias of calculated polarization varies with the noise-to-signal ratio. The darker curves are for the standard method, while the lighter are for the new method. The dashed curves are from numerical simulation, and the solid curves are from the expectation values of μ/I_θ.

4. The new data analysis method

To detect the polarization of faint sources correctly, we have to measure I_θ better. At South Pole in 2003, we found that the average standard deviation of atmospheric opacity (tau) measured by the 350μm tipper (Peterson et al. 2003) is .06 during one hour. This is so small that the change in the signal due to the tau fluctuation is negligible compared to that due to the sky noise fluctuation. In an hour, SPARO can obtain 9 polarimetic observations, which contain 6x9 measurements of I_θ. The weighted mean of these 54 values, I, will be used as the measurement of I_θ for any θ in any observation during this hour. The error, σ(I), is estimated by the standard deviation of the 54 values of I_θ divided by $\sqrt{54}$. For D_θ, let $R_{\theta k}$ ($T_{\theta k}$) be the sequence of the 12 frames from the kth step of the nod pair carried out at half-wave plate angle θ for a pixel in the R (T) array. Define $D_{\theta k}$ as $R_{\theta k}$-f$T_{\theta k}$ and its mean and variance as $\overline{D_{\theta k}}$ and $\sigma^2(D_{\theta k})$. We next compute

$$D_\theta = \Sigma_k g(k)\overline{D_{\theta k}},\ g = [1, -1, -1, 1]$$

and

$$\sigma^2(D_\theta) = \Sigma_k \sigma^2(D_{\theta k})/12$$

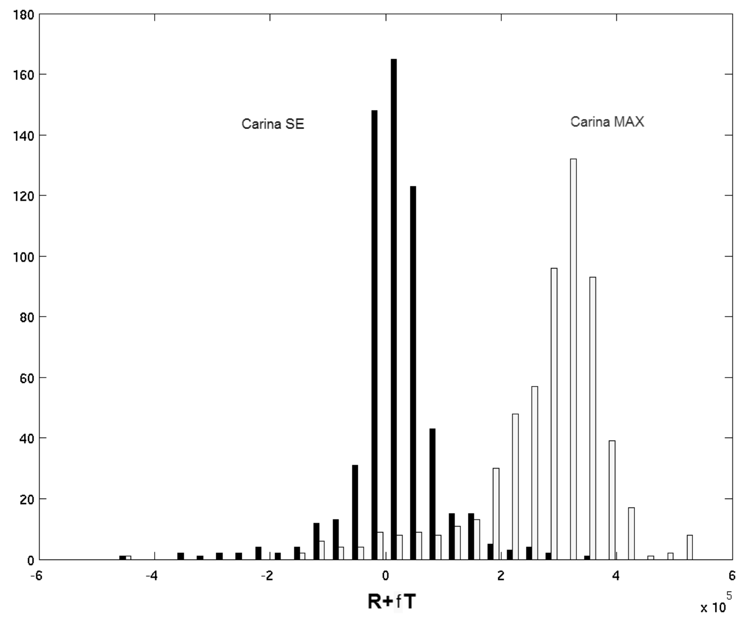

Figure 2. The histograms show the distributions of R+fT for the center pixel for each of two fields: CarinaMax and CarinaSE. R+fT is shown in a-to-d units.

So the polarization signals and their errors can be estimated by

$$S_\theta = D_\theta / I$$

and

$$\sigma(S_\theta) = \frac{\sqrt{\sigma^2(D_\theta) + S_\theta^2 \sigma^2(I)}}{I}$$

We have estimated the bias induced by sky noise for the new method, using the same techniques discussed in section 3.2 (Fig.1). The bias as a function of σ/μ is smaller and more constant than for the standard method. For the purpose of comparing the two methods on a real case, we consider the results obtained for a field located northeast of the peak of the northern Carina nebula, which has the typical brightness in comparison with the other fields we observed. The result is shown in Fig.3, where we can see that the new method gives higher degrees of polarization and more accurate measurements of the polarization directions.

5. Discussion

In conclusion, the new data analysis technique has three advantages:

(1) It gives more accurate measurements than the standard method, especially for faint sources.
(2) It has smaller bias for almost any value of signal to noise.
(3) It has a bias that is less variable than for the standard method. In other words, the bias does not vary as strongly when the value of σ/μ

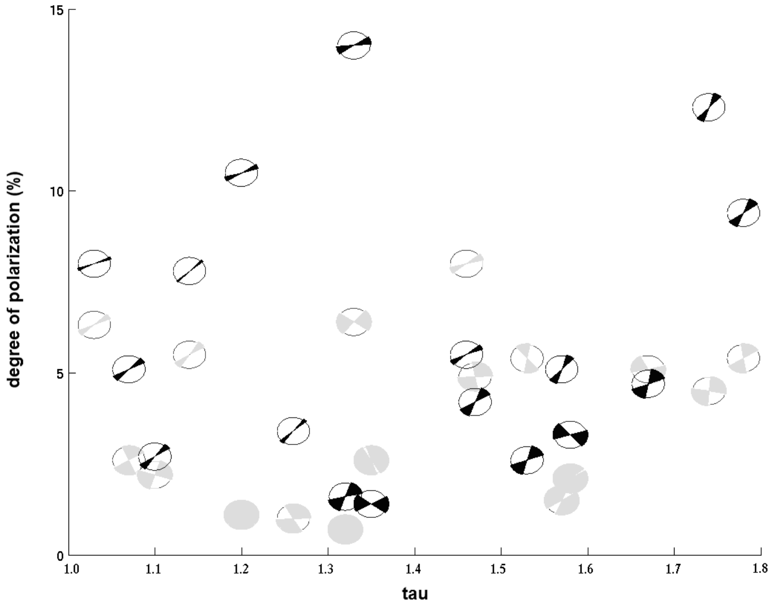

Figure 3. The angle of polarization with 1-σ uncertainty is indicated by the region within the circle that is shaded. The abscissa indicates the value of tau and the ordinate is the degree of polarization. Darker circles are for the new method. In comparison with the standard method that is shown using lighter circles, the dark circles give more accurate estimates of polarization direction, and larger degrees of polarization.

is changed. This is necessary for large-scale mapping, where μ varies a lot with position, and for the study of polarization spectrum, where σ varies a lot with wavelength.

Using our new method, SPARO detected approximately 200 3-σ polarization vectors, mostly concentrated in four GMCs: Northern Carina, G331.5-0.1, G333.6-0.2, and NGC6334. These sources contain some regions with $A_v \leq 10$.

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