POLARIMETRY WITH THE DIFFUSE INFRARED BACKGROUND EXPERIMENT ABOARD COBE

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ABSTRACT

This paper describes polarimetry of the Galactic plane and the zodiacal light,
surveyed by the COBE Diffuse Infrared Background Experiment. Methods of
analysis and the overall polarization characteristics of the diffuse sky are
emphasized over interpretation. Results are illustrated by polarimetry at 2.2 \micron
obtained from 1990 August 5-12, when most of the Galactic plane was in view.
Similar results are found at 1.2 \micron and 3.5 \micron.

I. INTRODUCTION

The Diffuse Infrared Background Experiment (DIRBE) is a cooled, off-axis
Gregorian telescope with a 19 cm primary mirror, designed to operate as an
infrared radiometer and polarimeter (Hauser et al. 1991; Boggess et al. 1992). It
has performed the first linear polarization survey of the diffuse sky from 1.2 \micron
to 3.5 \micron between November 1989 and September 1990.

Two large-scale sources of diffuse emission are expected to be polarized: the
Galactic plane and the zodiacal light. The Galactic plane is the brightest structure
in the sky in the near infrared. Its emission is largely due to starlight, polarized
through absorption by magnetically aligned dust grains. Polarizations of less than
\approx 1\% on average are to be expected (Martin and Whittet 1990). By contrast, the
zodiacal light is much fainter than the Galactic plane, but its polarization, due to
scattering of sunlight by grains close to the Earth, is expected to be as high as
\approx 10-15\% (Leinert 1975). This paper outlines the construction and operation of the
DIRBE polarimetry experiment, and describes the properties of the Stokes
parameters obtained with it.
II. CONSTRUCTION OF THE DIRBE POLARIMETER

DIRBE measures polarizations at 1.2 μm, 2.2 μm and 3.5 μm in bandpasses that approximate the ground-based J, K and L' filters. The construction of the polarimeter is different from that of most ground-based polarimeters, where a single polarizer is used at all wavelengths and samples the signal by rotating about the optical axis of the telescope. DIRBE is instead equipped with a three channel polarimeter for each wavelength. Channel 'a' is a total intensity channel and channels 'b' and 'c' contain polarizers whose principal transmission axes are orthogonal. Each channel sees the same instantaneous field-of-view of 0.7° x 0.7°. The polarizers are fixed inside the DIRBE: those in the 'c' channels are always parallel to the instrument scan direction on the sky, while those in the 'b' channels always orthogonal to the scan direction. The orientations at which these polarizers measure the sky are therefore dictated by the motion of the instrument field-of-view across the sky.

III. MEASUREMENT OF POLARIZATIONS WITH DIRBE

Linear polarization is described by the Stokes parameters Q and U, measured as fractions of the total intensity. They are defined in ecliptic coordinates relative to the local line of longitude: Q is the component parallel or perpendicular to the local line of longitude, and U is the component at 45°E or 45°W of the line of longitude. In this convention, positive values of Q are parallel to the line of longitude, positive values of U are 45°E of the line of longitude.

The principal advantage of having the polarizers fixed inside DIRBE is that all instrumental polarization effects are eliminated: the only polarization signal measured by DIRBE is that attributable to the sky. As the spacecraft scans, DIRBE records the polarizer orientation and the intensities in each channel at a time resolution of 1/8 sec. The orientation, θ, of the polarizer is defined as the angle between the local line of longitude and the polarizer axis in the 'c' channel projected on to the sky. It equals 0° when the polarizer is parallel to the local line of longitude, 90° when perpendicular to it. The "polarization signals" in channels 'c' and 'b', Yc,b, are related to the intensities via

\[ Y_c = (I_c/I_a)/k_c - 1; \quad Y_b = 1 - (I_b/I_a)/k_b \]

where \( I_c \) and \( I_b \) are the intensities, and \( k_c \) and \( k_b \) are the "polarization coefficients" for the 'b' and the 'c' channels. The coefficients take account of the efficiencies of the polarizers and the throughput of the DIRBE optics. They are found from the mean intensity ratios \( I/I_b \) and \( I/I_a \) of unpolarized calibration stars, such as Sirius. The Stokes parameters are related to \( y \) and \( \Theta \) via
\[ y_{c,b} = Q_{c,b} \cos(2\theta) + U_{c,b} \sin(2\theta) \]

Observations of each sky pixel (approximately 0.32° on a side) must be accumulated over one week to obtain adequate signal-to-noise. What governs DIRBE's ability to measure \( Q \) and \( U \) is the distribution of \( \Theta \) measured in one week, which is in turn governed by the DIRBE scan path. This important issue is amplified below.

IV. THE ORIENTATIONS OF THE POLARIZERS

Because the DIRBE field-of-view is inclined at 30° to the spin axis of the spacecraft, it traces out a helical path on the sky 60° wide, between solar elongation angles of 64° and 124°. Thus, the orientations change systematically across the scan path. At the edges of the scan path on the ecliptic equator, for example, the polarizers are perpendicular to the equator (i.e., parallel to the local line of longitude), and so have \( \Theta=0° \); these values increase progressively to \( \Theta=90° \) as the field-of-view rotates towards the middle of the scan path.

In one week, each sky pixel may be crossed while moving to the East or to the West of the local line of longitude, according to whether the field-of-view leads or follows the spin axis of the rotating spacecraft. Thus, successive orbits generally produce two distinct groups of orientations in each pixel. The range of \( \Theta \) within each group is, however, only a few degrees because the COBE orbit precesses 1° per day.

An important consequence of this narrow range of \( \Theta \) is that for most sky pixels, only one of the two Stokes parameters can be determined in one week. This applies to both the 'c' and 'b' channels: a consequence of having fixed orthogonal polarizers is that they both measure the same Stokes parameter; one channel does not, for example, measure \( Q \) while the other measures \( U \). \( Q \) is only determined where \( \Theta=0° \) or ±90°, and so is generally only measured at the edges of the sky path and in the middle. Only \( U \) is determined near \( \Theta=45° \). \( Q \) and \( U \) are therefore measured alternately as the spacecraft scans across the sky.

V. RESULTS: POLARIZATION OF THE SKY AT 2.2 \( \mu \)m

a) The Data

This section summarizes the Stokes parameters obtained from 1990 August 5-12, when most of the Galactic plane was in view. They were found in each channel by performing a robust least-squares fit to all the data obtained in each sky pixel (excluding data contaminated by the Moon, the planets or the South Atlantic Anomaly). The two independent measures of \( Q \) or \( U \) given by the 'c' and 'b' channels are then averaged by weighting each value according to its uncertainty.

All results quoted here are preliminary because photometric closure corrections have not been applied: the values of the Stokes parameters will change by a few
percent of those quoted here. Definitive weekly-averaged Stokes parameters Q and U for the whole mission will be part of the final data products released in June, 1994.

b) Discussion of Results

The 2.2 μm polarizations of the Galactic light and of the zodiacal light are very different. The zodiacal light is strongly polarized, with average Stokes parameters of Q=+10% and U=0%. The uncertainties per sky pixel are generally in the range $\sigma_Q/Q$ and $\sigma_U/U = 1\%$ to 15%, the wide variation arising largely because stars contribute to the photometric noise in the large DIRBE beams.

Galactic polarizations are much smaller than the zodiacal polarizations. The two can be easily distinguished between galactic longitudes of $l=\pm90^\circ$, where the Galactic emission is very strong. Here, the average amplitudes of Q and U are approximately 0.7%, in accord with the results of ground-based polarimetry (Martin and Whittet 1990). Within $l=\pm20^\circ$ of the Galactic Center, the polarizations correlate with the 1.25 μm optical depth. Moreover, the Barnard 78 dark cloud complex 3° north of the Center is also strongly polarized (Arendt et al. 1993).

The uncertainties in the Galactic Stokes parameters are generally very small, with $\sigma_Q/Q$ and $\sigma_U/U = 0.5\%$ per pixel. These values do not exhibit the wide fluctuations seen in the zodiacal light. This is because the many stars seen in each DIRBE beam make the signal appear spatially smooth on the scale of a DIRBE pixel. The direction of the polarization vector of the Galaxy is difficult to determine in this preliminary investigation: accurate determination will require the separation of the Galactic and zodiacal components. Analysis to perform this separation is planned.

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REFERENCES

Arendt, R. et al. 1993, this volume.
Leinert, Ch. 1975, Space Science Reviews, 18, 281.