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LINEAR AND CIRCULAR POLARIZATION OF THE COSMIC BACKGROUND RADIATION

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ABSTRACT

We have new data which consist of continued measurements of the linear polarization of the cosmic background radiation as well as the first measurement of the circular polarization. Eleven declinations have been surveyed for linear polarization and one declination for circular polarization, all at 9 mm wavelength. We find no evidence for either a significant linear or circular component with statistical errors on the linear component of 20–60 μK for various models. For linear polarization, a 95% confidence level limit of 0.1 mK (3×10^{-5}) for an axisymmetric anisotropic model is achieved, while for spherical harmonics through third order, a corresponding limit of 0.2 mK is achieved. For a declination of 37°, a limit of 12 mK is placed on the time-varying component and 20 mK on the DC component of the circular polarization at the 95% confidence level. At 37° declination, the sensitivity per beam patch (7°) is 0.2 mK.

Subject headings: cosmic background radiation — polarization

I. INTRODUCTION

In 1968 Rees suggested that an anisotropically expanding universe would produce a net polarization in the cosmic background radiation. Recently, Negroponte and Silk (1980) looked at a number of models and found typical polarizations of 1% to 100% compared to the induced radiation anisotropy. Reports of a quadrupole anisotropy at about 1 mK were added incentive to look at the polarization. Although new anisotropy data at 3 mm (Lubin 1982; Lubin, Epstein, and Smoot 1983) and at 12 mm (Fixsen 1982; Fixsen, Cheng, and Wilkinson 1983) do not show this quadrupole, it is still useful to look at the polarization since these ground-based measurements are more sensitive than the high-altitude anisotropy measurements due to the longer integration times possible from the ground. In addition, the polarization depends only on the intrinsic anisotropy and not on the locally induced dipole anisotropy which is apparently much larger than the intrinsic component and hence is a "background" in these measurements.

II. MEASUREMENT

The theory, instrumentation, and data analysis techniques used for this experiment have been described before (Lubin and Smoot 1979; Lubin 1980; Lubin and Smoot 1981) and are discussed only briefly. The instrument used for the linear polarization measurements is the same as was used previously and is shown in Figure 1. It is a 33 GHz (9 mm) radiometer which uses a Faraday rotator to switch between orthogonal linear polarization states. The antenna used is a very low sidelobe, corrugated, dual-mode scalar horn augmented by an additional ground shield to minimize ground pickup. The overall system sensitivity is 50 mK $\mathrm{Hz}^{-1/2}$ with a noise temperature of 500 K and a bandwidth of 500 MHz. The instrument is highly temperature stabilized to minimize gain variations with a typical change of 1 mK hr^{-1} in the instrument asymmetry (offset). The atmosphere which is essentially unpolarized at our wavelength has an emissivity of about 4%. The instrument rotates about the vertical axis to allow measurement of both linear polarization Stokes parameters, Q and U, and to remove any instrumental asymmetry.

To measure the circular polarization, Stokes parameter V, two methods were used. The first method used a screw-tuned quarter-wave plate (waveguide) between the antenna and the Faraday rotation switch. The inherent asymmetry, measured using a liquid-nitrogen–cooled unpolarized target, was approximately 1% (3 K) and was stable to within 10 mK over a day. The measured axial ratio was 0.4 debyes. The second method used a quarter-wave plate at the aperture of the antenna. The plate was constructed of a series of metal ribs arranged to give a 90° phase shift which converts circular polarization into linear polarization. Both methods gave a result consistent with no circular polarization. The first method has the advantage of not distorting the antenna pattern and of being well controlled thermally. The second method was used as an independent cross-check and to study the asymmetries in the quarter-wave plate since the apparatus can be rotated independently of the plate.

The circular polarization measurement is inherently more difficult to make than the linear one because of the different symmetry involved. In the linear case the inher-

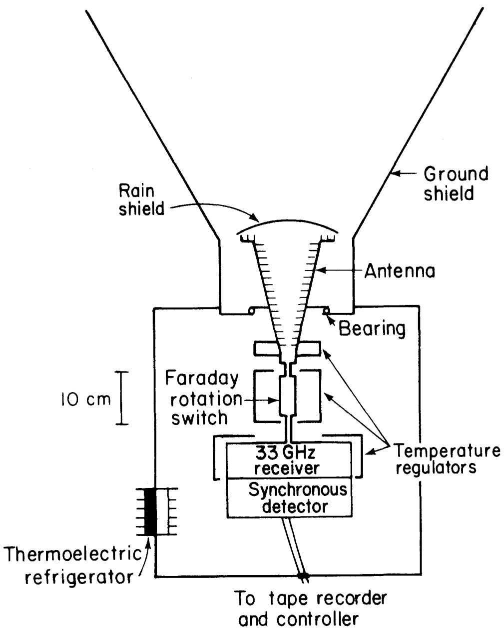

FIG. 1.—Microwave polarimeter used to measure linear polarization. Circular polarization was measured by two methods. In the first method, a tuned quarter-wave plate (waveguide) was put between the antenna and Faraday rotation switch. In the second method, a quarter-wave plate was placed at the aperture of the antenna.

ent asymmetry in the instrument (offset) can be canceled out to an extremely high degree by rotating the entire instrument about its axis. This interchanges the measured parameters Q and U while leaving the offset unchanged. For vertical observations, this process cancels the offset, which is typically 50 mK, to better than 1×10^{-3} with no indication of any residual. For the circular case, however, there is no corresponding apparatus-independent symmetry to cancel the offset. Using a known unpolarized target (cold or hot) will work, but this method relies on the *a priori* knowledge that the target is unpolarized. Searching for (sidereal) time variations is a way of avoiding the problem of absolute "DC" calibration, though this places stringent requirements on gain stability. The limit we place on the circular polarization reflects these difficulties. At this time, the linear polarization measurement is limited by statistics (observing time), although we are at a level where we believe the Galaxy may soon become a problem for global fits (Lubin and Smoot 1981). The circular polarization measurement, however, is limited by the systematic errors mentioned, at the 10 mK level.

III. RESULTS

We have been collecting data since 1978, although with a number of instrument revisions. Data have been collected in both the northern and southern hemispheres at 11 declinations, −37° to +63°, for linear polarization and at +37° declination for circular polarization. Linear polarization sky coverage is shown in Figure 2. The linear polarization data have been fitted to spherical harmonics through the third order and to an axisymmetric expansion model as well as to Fourier components at individual declinations. The spherical harmonic fits are summarized in Table 1 while the axisymmetric fit is given in Table 2. Except for a marginally significant fit of linear polarization to the axisymmetric model, we find no evidence of polarization in the cosmic background radiation. We set 95% confidence level limits of (1) 0.2 mK on spherical harmonics through third order, (2) 0.1 mK for the axisymmetric model for linear polarization, and (3) 20 mK for the non–time-varying (DC) component, and 12 mK for the first three Fourier components, of the circular polarization at 37° declination. The present sensitivity level per beam patch (7°) at 37° declination is 0.2 mK for linear polarization. Because the sky coverage was not uniform, some of the spherical harmonic components are significantly correlated with each other. Of the 272 correlation coefficients, only a few are above 0.2. These are primarily the Z-axis harmonics which are independent of right ascension, α, and have correlations of about 0.8.

Two other groups have made measurements of the linear polarization in the background radiation. The Princeton group made the first measurement in 1972 (Nanos 1974, 1979) at 3 cm, and in 1978 a group at Florence made a balloon-borne measurement at submillimeter wavelengths (Caderni *et al.* 1978).

The theoretical relationship between linear polarization and anisotropy has been studied by Rees (1968), Negroponte and Silk (1980), and Basko and Polnarev (1980). In general, the link is highly model dependent, so quantitative limits on global properties of the universe such as expansion anisotropy and shear from our data are meaningful only if a specific model is invoked. Two processes which can generate circular polarization are primordial magnetic fields, present at decoupling, and possibly an overall rotation of the universe. Thomson scattering prior to and during decoupling will tend to erase it however (Visser 1979).

IV. FUTURE STUDY

All indications are that the linear polarization measurement is not systematics limited and further study is warranted. At our wavelength, the Galaxy may be a problem in the future, although if the galactic plane is avoided, measurements down to 20 μK per pixel (7° beam size) at high galactic latitudes should be possible. At higher frequencies, the Galaxy is even less of a problem except for dust emission, the polarization properties of which little is known at mm wavelengths. New technologies such as superconducting device (SIS) re-

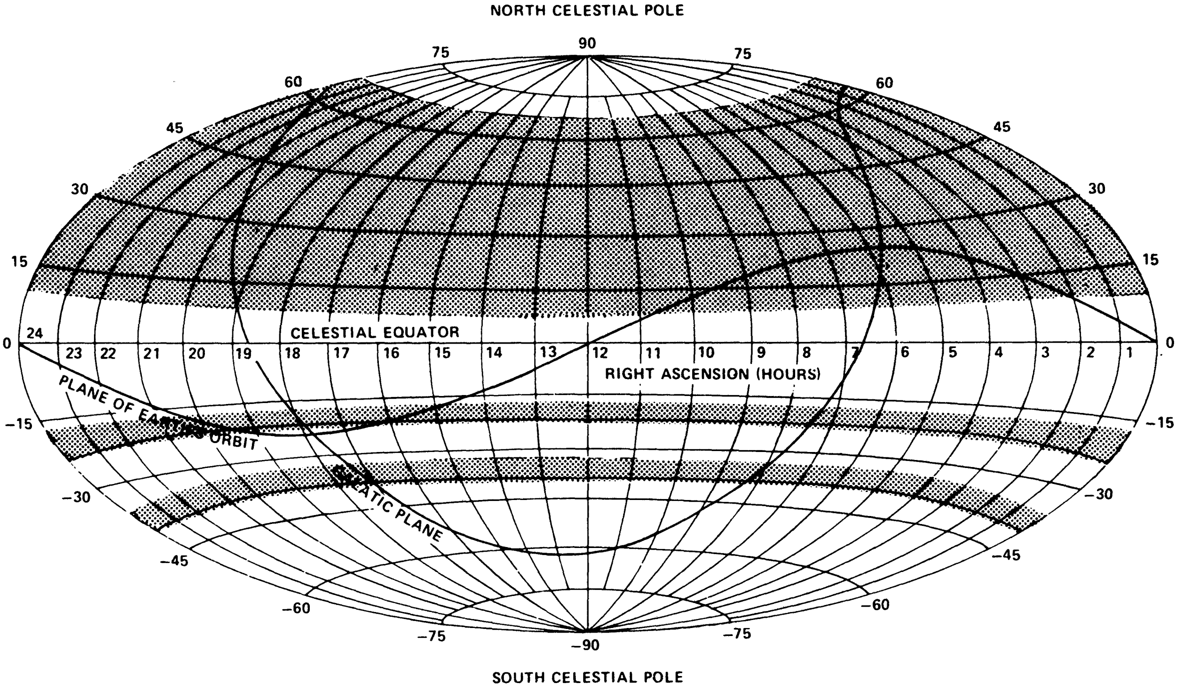

FIG. 2.—Sky coverage obtained for linear polarization measurement. Circular polarization data were taken only at +37° declination. Northern hemisphere data were taken from Berkeley, while southern hemisphere data were taken from Lima, Peru. Antenna beamwidth was 7°.

TABLE 1

LINEAR POLARIZATION SPHERICAL HARMONIC FITS—INDEPENDENT FITS BY ORDER (mK)

Fitting Function P_l^m	Q Fit	U Fit	Error
1	−0.02	0.04	0.02
$\sin\delta$	−0.04	0.07	0.03
$\cos\delta\cos\alpha$	−0.02	−0.03	0.04
$\cos\delta\sin\alpha$	−0.04	0.04	0.04
$\frac{1}{2}(3\sin^2\delta - 1)$	−0.04	0.07	0.05
$\sin 2\delta\cos\alpha$	−0.04	−0.04	0.03
$\sin 2\delta\sin\alpha$	−0.06	−0.01	0.03
$\cos^2\delta\cos 2\alpha$	0.06	0.03	0.04
$\cos^2\delta\sin 2\alpha$	−0.01	0.12	0.04
$\frac{1}{2}(5\sin^3\delta - 3\sin\delta)$	0.07	−0.01	0.06
$\frac{1}{4}\cos\delta(5\sin^2\delta - 1)\cos\alpha$	−0.02	−0.07	0.04
$\frac{1}{4}\cos\delta(5\sin^2\delta - 1)\sin\alpha$	−0.08	−0.05	0.04
$\cos 2\delta\sin\delta\cos 2\alpha$	0.01	0.04	0.03
$\cos 2\delta\sin\delta\sin 2\alpha$	0.00	0.06	0.03
$\cos^3\delta\cos 3\alpha$	0.03	0.09	0.05
$\cos^3\delta\sin 3\alpha$	0.03	−0.02	0.05
	Q: χ^2/DOF	U: χ^2/DOF	
1	304/287 CL = 24%	316/287 CL = 12%	
Dipole	301/285 CL = 25%	322/285 CL = 7%	
Quadrupole	297/283 CL = 28%	312/283 CL = 12%	

ceivers may make much more sensitive surveys possible in the near future. A high-altitude survey with an instrument at about 3 mm wavelength where the galactic emission is small (Lubin, Epstein, and Smoot 1983) may allow measurements of linear polarization at the μK level. With beam-switching techniques, the circular polarization could be measured much more accurately although this method would not measure the DC level.

TABLE 2

FIT TO ANISOTROPIC AXISYMMETRIC MODEL (Rees 1968)

Parameter	Prediction of Model[a]
Q	$(T_w - T_a)_{\max}[\cos^2\delta(1 - 3/2\sin^2\theta_0) + \sin 2\theta_0 \cos\delta \sin\delta \sin(t - \alpha_0 - \pi/2) + \sin^2\theta_0(1 - 1/2\cos^2\delta)\sin 2(t - \alpha_0 + \pi/4)]$
U	$-(T_w - T_a)_{\max}[\sin 2\theta_0 \cos\delta \sin(t - \alpha_0 + \pi) + \sin^2\theta_0 \sin\delta \sin 2(t - \alpha_0)]$
	Least Squares Fit to Model
$(T_w - T_a)_{\max}$	-0.06 ± 0.03 mK
θ_0	$35 \pm 15°$
α_0	14 ± 1 hr
χ^2/DOF	615/573
CL	11%

[a] θ_0 = angle from celestial pole to symmetry axis of the universe; α_0 = right ascension of symmetry axis of the universe.

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