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An Upper Limit on the Contribution of Galactic Free-Free Emission to the Cosmic Microwave Background Near the North Celestial Pole

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ABSTRACT. We have observed the region of the sky north of 81° declination with a wide-angle CCD camera and narrow-band (1 nm) Hα filter. After subtracting the stellar background using off-band images and smoothing to 0°.1 resolution, we set an upper limit on the anisotropy in the Hα emission at this angular scale of 1.3 Rayleigh. At degree angular scales, the upper limit is 0.5 R, which corresponds to an anisotropy in the brightness temperature of the free-free emission at 32 GHz of 3 μK. Thus no more than 7% of the 44 μK anisotropy observed by Netterfield et al. (ApJ, 331, 341, 1995) can be due to free-free emission by Galactic hydrogen.

1. INTRODUCTION

Over the last few years, highly accurate observations of the cosmic background radiation at a number of radio frequencies have been obtained with ground-based radio telescopes and with the *COBE* satellite. Considerable effort is being expended to measure the anisotropy in this background. Galactic free-free radiation, contributed by the interstellar medium's diffuse ionized phase, has become a potentially limiting factor in such studies. Although the signal is small, its unknown contribution from place to place on the sky is the dominant uncertainty, particularly for those studies attempting to measure anisotropies at the small angular scales so important for testing theoretical models of the formation of structure in the early Universe. Luckily this same ionized gas emits optical line radiation from recombining hydrogen atoms, the Hα line in particular, which, although of very low surface brightness, is readily detectable with simple instrumentation. An Hα surface brightness is easily transformed to a predicted radio free-free contribution to the cosmic background signal with the relation (Bennett et al. 1992)

$$\frac{T_A(\mu\mathrm{K})}{I_{\mathrm{H}\alpha}(R)} = 1.89\frac{[1-0.151\ \ln(\nu/53\ \ \mathrm{GHz})]}{(\nu/53\ \ \mathrm{GHz})^2} \qquad (1)$$

where T_A is the microwave antenna temperature in microkelvins and $I_{\mathrm{H}\alpha}$ is the Hα surface brightness in Rayleighs. (One Rayleigh = $10^6/4\pi$ photons cm^{-2} s^{-1} ster^{-1} and corresponds to an emission measure EM$\approx$2 cm^{-6} pc; the faintest emission nebulosities visible on the original Palomar Observatory Sky Survey red plates are at a level of approximately 100 R.) With the instrumentation described below we can detect Hα emission as faint as about 1 R, which corresponds to free-free emission with a brightness temperature of 2 μK at 53 GHz (one of the *COBE* bands) and 15 μK at 20 GHz (the frequency of one of the longer-wavelength ground-based radio surveys), compared to claimed detections of anisotropies at the tens of μK level.

Results for some fields near the North Celestial Pole, where some of the background measurements are made (Readhead et al. 1989; Cheng et al. 1994; Netterfield et al. 1995), were reported by Gaustad et al. (1995). The extension to the entire region of the sky north of declination 81° was first reported by Farny and Khosrowshahi (1995), and is described here in more detail. Simonetti et al. (1996) have published a very-wide-angle Hα image of the north polar region, from which they derive conclusions similar to ours.

2. INSTRUMENTATION AND SITE

Our instrumentation is similar to the "parking lot camera" of Bothun and Thompson (1988) and to the system used by McCullough et al. (1990). The detector is a Photometrics CCD camera with a PM512 chip (a 512×512 array with 20 μm pixels), thermoelectrically cooled to about −40 °C, and controlled by a Macintosh IIci computer. We image the sky onto the chip with an 85-mm *f*/1.8 Nikon lens, giving a 7°×7° field of view with a scale of 0.8 arcmin pixel^{-1}. A two-inch diameter 1.0-nm bandwidth Hα

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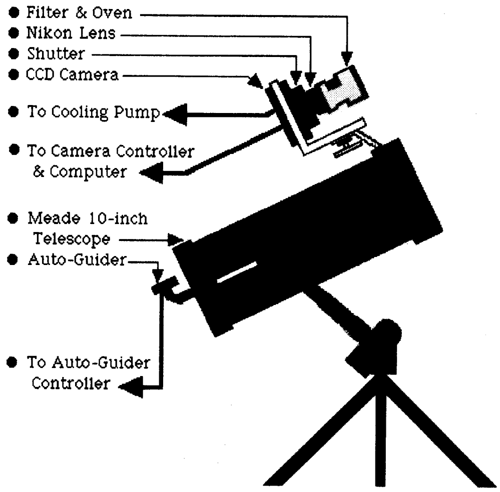

FIG. 1—Instrumental setup. The CCD camera, lens, and filters are mounted piggy-back on a portable 10-inch reflector, which serves as a finder and guide telescope.

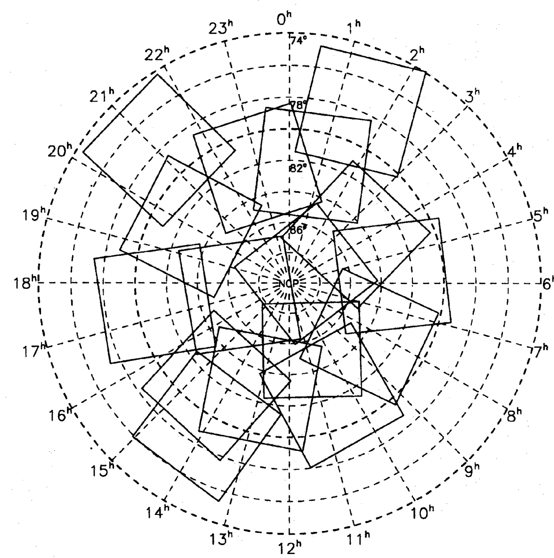

FIG. 2—Map of North Celestial Pole region showing fields observed.

filter, housed in an oven kept at 30 °C to control the central wavelength, is mounted in front of the lens. This bandwidth was chosen to minimize the sky background, yet provide adequate transmission of Hα light at the edges of the field. We also take images with off-band filters to subtract the star and sky background. Since the stars have differing colors, we use two such filters, of 3-nm bandwidth, to interpolate the continuum to 656.3 nm. These filters are not temperature controlled and are centered at 643.5 and 675.5 nm, wavelengths which fall between the night-sky emission lines of the 6-1 band of OH (Chamberlain 1961). The CCD camera, lens, and filters are mounted piggy-back on a portable 10-inch reflector (Fig. 1), which serves as a finder and guide telescope. We use another small CCD for autoguiding.

The key limit to sensitivity of our system is the brightness of the background sky. In a pilot study we tested the instrument at several sites, and found that the sky near Hα is half as bright at observatories in the Southwest as at rural East Coast sites, and one-tenth as bright as at Swarthmore's suburban Philadelphia location. The darkest sites tested (Apache Point Observatory in New Mexico and Mount Laguna Observatory near San Diego) have a sky brightness of about 3.8×10^{-18} erg cm^{-2} s^{-1} sr^{-1} Hz^{-1} (21.6 mag arcsec^{-2}, 11 R nm^{-1}), similar to the value 4.5×10^{-18} erg cm^{-2} s^{-1} sr^{-1} Hz^{-1} measured by Shectman (1974) twenty years ago at Palomar.

3. OBSERVATIONS AND DATA REDUCTION

The observations reported here were obtained at Mount Laguna Observatory on eight nights from 1994 December through 1995 July. Sixteen fields were observed, covering (with one small exception) the entire region north of 81° declination (Fig. 2 and Table 1). Field centers were generally chosen to be close to those used for the Palomar Sky Survey, the actual centers being dictated by availability of a suitably bright guide star. Several times in each observing run we also observed fields containing H II regions of known surface brightness for the purpose of intensity calibration.

For each field we generally took ten exposures of 5 min each with the Hα filter, plus five exposures of 2 min each with each of the off-band filters. These exposure times were chosen so that the photon noise in the images is greater than the CCD readout noise. Ten dark exposures of 5 min each were taken once each night, generally five at the beginning and five at the end, as well as several bias readouts. Once per night the Hα filter transmission (as a function of position in the field) was calibrated by taking several images of a light box covered with a screen of translucent paper and illuminated by a hydrogen lamp. The same light box, illuminated by a white-light continuum source, was used for obtaining flat-field images for all three filters.

TABLE 1
Fields Observed

	Field center				
Name	α (2000)	δ	l	b	Date
0100+83	00^h43^m	82°2	122.6	19.3	1995 July 23
0132+78	01^h29^m	78°1	124.9	15.3	1995 July 28
0230+84	03^h35^m	84°7	126.7	23.1	1994 December 30
0232+89	04^h04^m	88°8	124.0	26.3	1995 January 1
0500+84	05^h45^m	83°3	130.0	25.0	1995 January 1
0730+84	08^h15^m	83°8	129.6	29.2	1994 December 30
1000+84	10^h38^m	82°3	128.0	33.5	1994 December 30
1230+84	13^h00^m	82°9	122.6	34.2	1995 January 1
1420+87	10^h46^m	85°4	125.7	31.0	1995 July 24
1500+84	14^h21^m	81°9	119.2	34.6	1995 May 23
1520+79	13^h59^m	79°4	119.1	37.2	1995 July 26
1730+84	17^h25^m	81°2	113.5	30.0	1995 May 25
2000+84	19^h58^m	82°6	115.2	24.8	1995 May 23
2020+87	17^h04^m	86°7	119.6	28.6	1995 July 24
2128+78	21^h02^m	78°1	112.3	20.3	1995 July 26
2230+84	22^h59^m	82°3	119.1	20.3	1995 May 25
139 Tau	05^h52^m	27°0	182.3	0.1	1994 December 30
NA Nebula	20^h55^m	43°9	84.8	−0.7	1995 May 25

Image processing was done on a DECStation 5000 workstation, using software written in IDL (from Research Systems, Inc.). In most cases the images could be simply coadded pixel by pixel. Cosmic-ray events were eliminated by discarding values which deviated by more than 3.5 times the average deviation from the median calculated for each pixel, then calculating the mean of the remaining values. (Typically, 5% of the total were rejected by this criterion as being cosmic-ray hits; never were fewer than three good images available for averaging at a given pixel location after these rejections.) The mean of the dark exposures, similarly treated for cosmic-ray hits, was then subtracted.

In the few cases for which field rotation occurred, due to misalignment of the polar axis, a mean dark exposure was subtracted first from the individual images, which were then aligned by shifting and rotating so as to minimize the differences in centroid positions of at least 40 stars. The resulting aligned images were then coadded as above.

Next each coadded image was divided by a mean white-light flat image (with bias subtracted) for the appropriate filter. In a few cases good white-light flats were not available. Because the filters are so close in wavelength, the response of the CCD is very similar in all three filter bands, and the lack of flattening in these cases was not apparent in the final subtracted images.

The next step was to remove the stars and continuum sky background. No matter how good the polar alignment, the coadded off-band images were never coaligned perfectly with each other or with the coadded Hα image, probably because of shifts caused by slight deviations from flatness in the filters. Thus they were first shifted and rotated as described above to produce alignment, and the two off-band images averaged. The intensity scale factor between this image and the Hα image was determined by averaging the difference in instrumental magnitudes for the alignment stars. After multiplying by this scale factor, the average off-band image was subtracted from the Hα image.

This procedure removed the sky background and most star images fairly well. It cannot be expected to work well, however, for stars which have strong Hα absorption or emission lines in their spectra. Also, slight differences in curvature in the filters can produce differences in focus of one image with respect to another, resulting in different image profiles. No attempt was made to correct for this. Instead, the continuum-subtracted image was smoothed with a median filter 7 pixels on a side, reducing the angular resolution from 0.8 to 5.6 arcmin, about 0°.1. The smoothed images still contain some defects near the positions of very bright stars, most of which can be traced to ghosts resulting from multiple reflections within the filters.

These images also contain a residual background continuum, the broad Hα emission from the earth's geocorona, which is contained within the bandpass of the Hα filter but not in the off-band filters. The average value of this background was obtained by finding the mode of the brightness distribution of several thousand pixels, and subtracted out. This sky component varied from night to night, ranging from 9 to 37 *R* (Table 2). Thus our final images cannot be combined to show low-contrast structures larger than the 7° diameter of a single field, but they can be used to show smaller structures and anisotropies on the scale of tenths of a degree to a few degrees in angular size.

TABLE 2
Hα Sky Brightness (*R*) at 0°.1 Resolution

Region	Sky brightness	rms deviation (1σ)
0100+83	27.9	1.7
0132+78	21.6	1.8
0230+84	15.7	0.9
0232+89	10.5	0.6
0500+84	15.7	0.7
0730+84	9.2	0.9
1000+84	22.3	1.8
1230+84	29.0	1.3
1420+87	36.8	1.7
1500+84	33.4	1.9
1520+79	20.1	1.3
1730+84	30.2	1.5
2000+84	35.3	1.5
2020+87	37.0	1.0
2128+78	20.7	1.3
2230+84	29.9	2.3
Mean	24.7	1.3

The next step is to take out the transmission function of the filter for a narrow line source, as determined by measuring the response to a flat-field screen illuminated by a hydrogen lamp. This is a smooth function of position in the field, and amounts to a correction averaging less than 14% across the field.

Intensity calibration, the conversion of computer units of surface brightness to Rayleighs, was accomplished by taking images of H II regions of known surface brightness and subjecting them to the identical image-processing procedure. In the winter season, we used the H II region surrounding 139 Tau, in the summer the North America Nebula, which have surface brightnesses of 17 and 850 *R*, respectively (Reynolds 1988). In each case we measured the average brightness, in computer units, on the final smoothed image with an circular aperture of angular diameter as given in Reynolds' paper, centered on the brightest part of the nebula, subtracted the brightness of a similarly sized region in the darkest part of the image, and then applied Reynolds' measured values to get the conversion factor.

4. RESULTS

The final image of one of the fields, centered at $5^h45^m+83°.3$, is shown in Fig. 3, and the image of one of the calibration regions, centered at $5^h52^m+27°.0$ in Fig. 4. All of the final images are available via anonymous ftp from puck.astro.swarthmore.edu (130.58.68.19) or via the World Wide Web from www.ipac.caltech.edu/HalphaSurvey.

The large circular region on the lower left (southeast) in Fig. 4 is an H II region surrounding the B0.5 II star 139 Tau. It is one of the regions we used to calibrate the intensity scale, and has a brightness of 17 *R* (Reynolds 1988). It is not visible on the Palomar Sky Survey prints. The small circular object in the center of the image is the compact H II region S 242 (Sharpless 1959), with a brightness of 180 *R* (overexposed in this print). In the upper right is part of the super-

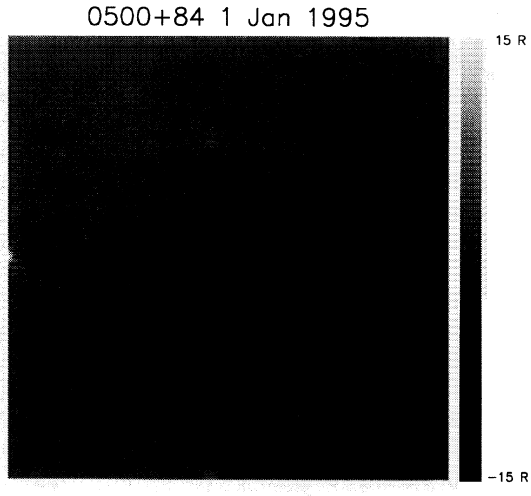

FIG. 3—Hα image of the 0500+84 field, 7° square, centered at α=5^{h}45^m, δ=83°3 (2000). Stars have been removed by continuum subtraction and smoothing to 0°1 resolution. North is up and east to the left. All residual bright areas can be attributed to ghosts or imperfectly subtracted bright stars. The object just at the eastern edge of the field is the residual image of HR 2742 (VZ Cam).

nova remnant S 147. The faint features visible on this image illustrate the possibility of using this type of imaging technique for studying structure of the interstellar medium, the subject of future papers.

In the North Celestial Pole region, only one faint H II region is seen, S 174 at 23^{h}46^m+80°9, with an angular diameter of about 10′ and an average surface brightness of about 17 *R*. Otherwise the structure is extremely smooth; all other bright spots can be identified as ghosts of bright stars. The root-mean-square deviations from the mean for each field are listed in Table 2. The average for all fields is 1.3 *R*. We suspect that most of the observed deviations from the mean

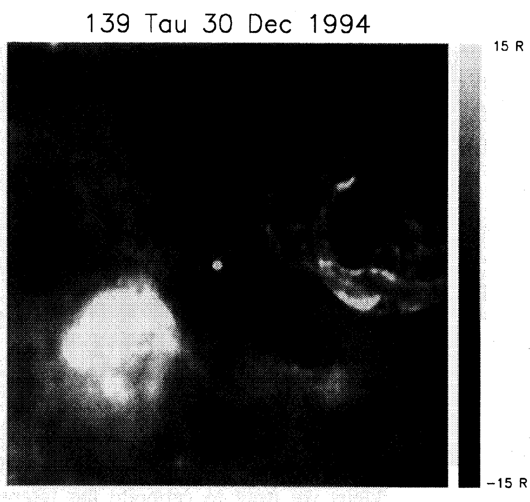

FIG. 4—Hα image of the 139 Tau field, 7° square, centered at α=5^{h}52^m, δ=27°0, and reduced in the same way as for Fig. 3. The large circular region on the lower left (southeast) is the H II region surrounding the star 139 Tau. It has a brightness of 17 *R*. The small circular object in the center of the image is the compact H II region S 242, with a brightness of 180 *R*. In the upper right is part of the supernova remnant S 147.

TABLE 3
Double-Difference-Beam Anisotropies
(Diameter 1°4, Throw 2°45, Center δ=85°1)

Region	Hα(*R*)	Inferred Free-Free at 32 GHz (μK)
0100+83	−0.56±0.50	−3.6±3.2
0230+84	−0.10±0.26	−0.6±1.7
0500+84	−0.13±0.04	−0.8±0.3
0730+84	−0.23±0.13	−1.5±0.8
1000+84	−0.24±0.40	−1.5±1.2
1230+84	−0.07±0.40	−0.4±2.6
1500+84	−1.17±0.09	−7.5±0.6
1730+84	−0.44±0.16	−2.8±0.2
2000+84	−0.95±0.16	−6.1±1.0
2230+84	−0.66±0.15	−4.2±0.9
Mean	−0.45±0.19	−2.9±1.2

are instrumental in origin, so we conclude that the intrinsic anisotropy at 0.1 degree angular scale in the region north of declination 81° is less than 1.3 *R*.

5. COMPARISON WITH CMBR MEASUREMENTS

Netterfield et al. (1995), in the experiment known as Saskatoon, have observed the cosmic microwave background radiation (CMBR) at six frequencies ranging from 26 to 46 GHz. The beam diameter for the K_a band (26–36 GHz) is 1°42. Their analysis procedure produces in effect a double-difference chopping, centered at declination 85°1, with a beam throw of ±2°45. Their measurements of brightness anisotropies as a function of right ascension, reproduced in Fig. 5 (the dashed lines), average 44 μK, with a peak at 5^h of about 100 μK. To simulate their observing procedure, on each of our fields in the 84° declination band we measured the average brightness within a circle of diameter 1°4 at 84° declination and four different right ascensions, subtracting 50% of the brightness within similar circles displaced north and south by 2°45. The results are listed in Table 3 and plotted in Fig. 5. The average over the entire 84° band

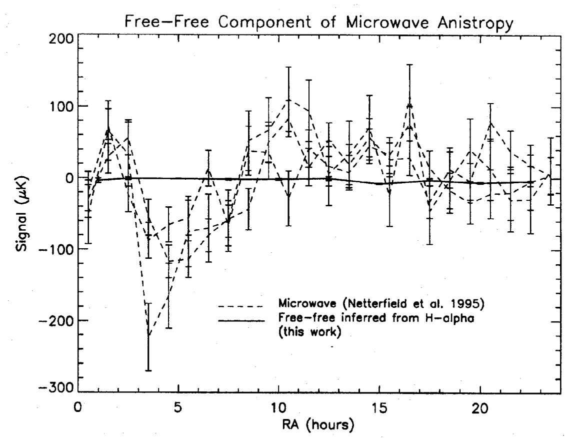

FIG. 5—Comparison of the anisotropies in the cosmic microwave background (dashed lines) at δ=85° measured by Netterfield et al. (1995) with the anisotropies in the free-free emission (solid line), as inferred from the Hα imaging of this paper using a similar double-difference-beam measurement.

around the pole is -0.5 ± 0.2 *R*, which translates, using Eq. (1), to -3.0 ± 1.2 μK at 31 GHz, the average frequency of the Netterfield et al. observations. Thus we conclude that no more than 7% of the 44 μK anisotropy observed in the Saskatoon experiment can be due to free-free emission by Galactic hydrogen. To put it in another, more striking way: if the 100 μK anisotropy in the microwave radiation at right ascension $5^{\rm h}$, shown in Fig. 5, were due to Galactic free-free emission, we would have seen anisotropies in the Hα emission in this region of ±17 *R*, as bright as the H II region around 139 Tau illustrated in Fig. 4. Clearly there are no such brightness variations shown in Fig. 3, and the Saskatoon microwave observations cannot be significantly contaminated by Galactic free-free emission.

Similarly, Cheng et al. (1994) claim detection of anisotropies of order 80 μK at $0\overset{\circ}{.}5$ angular scale in the range $\alpha=14.5^{\rm h}-20.5^{\rm h}$ at $\delta=82°$. At their largest frequency (168 GHz) our limit to the Hα brightness of 0.5 *R* translates to a limit of 0.05 μK on the contamination by free-free emission, which is completely negligible. Readhead et al. (1989), observing at 20 GHz, set an upper limit of 60 μK to the anisotropy at $0\overset{\circ}{.}1$ angular scale near $\delta=89°$. At their frequency and angular scale our limit on free-free emission is about 8 μK.

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