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HIGH-LATITUDE H I STRUCTURE AND THE SOFT X-RAY BACKGROUND

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ABSTRACT

We present 21 cm observations made with the NRAO 43 m (140 foot) telescope of 20 randomly selected intermediate and high galactic latitude regions. The data are examined for evidence of the neutral gas clumping required by models in which a substantial fraction of the diffuse soft X-ray background ($0.1 < h\nu < 0.284$ keV) originates outside the galactic disk and is absorbed by interstellar gas. We find no such evidence, and we conclude that the degree of clumping required by such models must, if it exists, have characteristic angular scales less than 14′. Furthermore, an analysis of other data indicates that the required clumping does not exist on smaller size scales. It is therefore unlikely that a significant fraction of the X-ray flux originates in a galactic corona, unless some other explanation of the anomalously small apparent absorption can be found.

Subject headings: radio sources: 21 cm radiation — X-rays: general

I. INTRODUCTION

Early work on the soft X-ray background revealed an anticorrelation between soft X-ray intensity and the neutral hydrogen column density inferred from 21 cm measurements (Bowyer, Field, and Mack 1968; Bunner *et al.* 1969). A naive explanation is that the soft X-rays originate outside the Galaxy and are absorbed by galactic gas. Although a truly extragalactic origin seems unlikely on observational grounds (McCammon *et al.* 1976, and references therein), a substantial fraction of the soft X-ray background could arise from a hot, low-density galactic corona surrounding the galactic disk. Spitzer (1956) first suggested that such a corona would provide pressure equilibrium for clouds observed at large distances from the galactic plane. Recent *IUE* observations (Savage and de Boer 1981) have discovered highly ionized gas far from the plane, and theoretical work (Chevalier and Oegerle 1979; Bregman 1980) predicts gas with temperatures between 3×10^5 and 2×10^6 K. Such gas is a source of thermal X-rays.

There are quantitative problems, however, in explaining the neutral hydrogen anticorrelation by absorption of coronal X-rays. The X-ray intensity variations are not, on the average, as large as predicted by the transmission variations calculated from H I column densities and normal elemental abundances (Bowyer and Field 1969; Bunner *et al.* 1969, 1970; Davidsen *et al.* 1972; Burrows 1982; Marshall and Clark 1984). Further, the X-ray variations are almost independent of energy, while photoelectric absorption cross sections show an E^{-3} dependence.

An attractive explanation for the small apparent absorption cross sections is that variations of gas column density on angular scales unresolved by 21 cm surveys reduce the predicted absorption (Bowyer and Field 1969; Bunner *et al.* 1969, 1970; Davidsen *et al.* 1972; Burrows 1982; Marshall and Clark 1984). When there are column density variations, the average transmission is greater than the transmission calculated for the average column density: $\langle \exp(-\sigma N_H) \rangle > \exp(-\sigma \langle N_H \rangle)$. Column density variations large enough to reduce the apparent cross sections to the levels required by coronal origin models result in an interstellar medium (ISM) that, to soft X-rays, is a mixture of transparent and almost completely opaque lines of sight. Column density variations therefore provide naturally the otherwise rather remarkable lack of energy dependence observed in the anticorrelation of soft X-rays with H I column density.

Although clumping of the interstellar gas provides a natural explanation for the observed behavior of the small apparent X-ray absorption cross sections, the degree of clumping required is large, and there is little evidence from 21 cm measurements or UV interstellar absorption data that it exists. The effective cross sections, σ_x, from X-ray model fitting, are determined primarily by regions where the apparent optical depth to soft X-rays is near unity. This corresponds to average H I column densities of 2–4 $\times 10^{20}$ cm^{-2}. The column density variations due to the clumping required by the coronal origin models would be approximately 100% and should be readily observable with adequate angular resolution. The Hat Creek 21 cm survey (Heiles and Habing 1974) was made with a 37′ beam and should be sensitive to clumping on all angular scales larger than about a degree. An analysis of many randomly selected fields from that survey has shown that the observed column density variations are far too small to reduce the effective absorption cross sections to the levels required by the coronal origin model (Burrows 1982). Extensive radio searches for structure on smaller scales have also been negative (Greisen 1976; Dickey 1977, 1979; Dickey and Terzian 1978; Dickey, Salpeter, and Terzian 1979; Payne, Salpeter, and Terzian 1983), and interstellar column densities derived from Lyman-α

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absorption measurements toward stars near each other in direction and distance do not show large fluctuations (Bohlin, Savage, and Drake 1978).

In spite of this lack of positive evidence, we wish to be careful about ruling out an otherwise straightforward explanation of the soft X-ray results that includes the physically reasonable and interesting concept of a strong X-ray corona. We have therefore examined the existing data for evidence of the required clumping on any physically reasonable angular scale. The Hat Creek survey data indicate that almost all of the structure would have to be on scales less than 1°, while an analysis of some of the small-scale 21 cm data (as described in § V) can be used to rule out scales below 20′. The case is weakest for the intermediate size range of 20′ to 1°. In this paper we present new 21 cm observations sensitive to this angular range and examine whether there is any observational support for extreme H I clumping.

II. THE X-RAY CONSTRAINTS

Burrows *et al.* (1984) have considered the soft X-ray data from the Wisconsin sky survey (McCammon *et al.* 1983) in the context of a two-component model in which a substantial fraction of the soft X-ray intensity originates in a galactic corona. A second, local, X-ray source (assumed to be isotropic and unabsorbed) is necessary to explain the X-ray intensity observed near the galactic plane, where the H I column density is many optical depths to soft X-rays. In the case considered here, the coronal component is assumed to be isotropic prior to absorption by interstellar gas, but more realistic models in which the source is flattened into a disk do not improve the fits to the observations. The contribution of the corona is assumed to vary as $\exp(-\sigma_x \langle N_H \rangle)$, since photoelectric absorption is the only important process in the radiative transfer of soft X-rays. Here $\langle N_H \rangle$ is the 21 cm H I column density from the survey of Stark *et al.* (1984) averaged over the X-ray field of view and σ_x is an arbitrary effective absorption cross section. The intensities of the two source components and the global value of σ_x are adjusted to give the best fit to the X-ray observations. The best fit values for σ_x are 0.52×10^{-20} cm^2 per neutral hydrogen atom in the C band ($0.16 < h\nu < 0.284$ keV) and 0.65×10^{-20} cm^2 for the lower energy B band ($0.13 < h\nu < 0.188$ keV). These are respectively about two-thirds and one-third of the total photoelectric cross sections, calculated for gas with the normal relative abundance of helium. We will use the symbol α to refer to the ratio of effective to atomic cross section. The Burrows *et al.* (1984) effective cross section results are summarized by $\alpha_B = 0.37$ and $\alpha_C = 0.65$.

Since 21 cm measurements are used to estimate the total gas, the possible presence of molecular or ionized hydrogen could cause systematic errors in the derived total gas column densities and the calculated effective cross sections. Significant amounts of H_2 would only make the quantitative problems with the two-component model worse, however, since the absorption would then be even larger than predicted from the H I measurements. If the observed variations in the 21 cm column density are caused by variations in the fraction of the hydrogen that is ionized and not by variations in the total gas column density, the absorption cross sections derived from X-ray model fitting would be just the hydrogen absorption cross sections. The best fit value for σ_x in the B band is approximately equal to the hydrogen absorption cross section which is about one-third of the total photoelectric cross section for gas with normal abundances (Morrison and McCammon 1983). However, the presence of H II cannot simultaneously explain the B and C band results.

Calculation of the expected absorption also involves the relative elemental abundances. For soft X-rays, however, only hydrogen and helium are significant absorbers. A near-zero helium abundance would be required to give approximate agreement with the observed B band variations but would result in too little predicted absorption in the C band.

Large column density fluctuations in gas that absorbs X-rays, on the other hand, would provide a natural explanation for both the reduced absorption cross sections and the near energy-independence of the X-ray intensity variations. An effective cross section, σ_{eff}, which accounts for column density variations, and α, the ratio of σ_{eff} to the photoelectric cross section, are defined by:

$$\alpha = \frac{\sigma_{\text{eff}}}{\sigma} = \frac{-\ln\left[(1/n)\sum_i \exp - \sigma(N_H)_i\right]}{\sigma(1/n)\sum_i (N_H)_i}, \tag{1}$$

where the sums run over a statistically adequate sample of n lines of sight in a particular spatial region. These quantities correspond to the σ_x and α derived from X-ray model fitting only if column density variations are responsible for the small observed values of σ_x. The variations in H I column density can be studied with 21 cm measurements, and in the rest of this paper we examine whether the low values of σ_x can be explained by low values of σ_{eff}.

If we assume that any line of sight intersects an integral number of discrete clouds, we can rearrange equation (1) to obtain

$$e^{-\sigma_{\text{eff}}\langle N_H \rangle} = \sum (P_n e^{-\sigma n N_C}), \tag{2}$$

where $\langle N_H \rangle$ is the average column density, N_C is the column density per cloud, and P_n is the probability of n clouds along a particular line of sight. For randomly distributed clouds of constant column density, this equation can be solved analytically for σ_{eff}. We assume the number of clouds along each line of sight to be Poisson distributed about its mean, which must be equal to $\langle N_H \rangle / N_C$. Solving equation (2) for σ_{eff} then yields

$$\sigma_{\text{eff}} = \frac{1}{N_C}(1 - e^{-\sigma N_C}). \tag{3}$$

Taking values for σ_B and σ_C from Burrows *et al.* (1984), we find that a random distribution of clouds of constant column density $N_C = 1.3 \times 10^{20}$ atoms gives $\alpha_B = 0.39$ and $\alpha_C = 0.63$, in accord with the requirements of the two-component model. This result also agrees fairly well with earlier results based on C band measurements alone (Bowyer and Field 1969; Bunner *et al.* 1969, 1970; Davidsen *et al.* 1972; Marshall and Clark 1984), which generally required slightly thicker clouds.

We note that the net transmission of two overlapping sheets of gas with the same type of cloud structure (but independent individual clouds) is simply the product of the transmissions of the individual slabs. Therefore, the reduction in effective cross section and value of α depend only on the properties of individual clouds and not on the average total column density.

Although the values of α determined from 21 cm measurements are insensitive to average column density, the apparent cross sections obtained from a global fit of the X-ray data to a two-component model are largely determined in regions where the apparent optical depth to soft X-rays is near unity. If the small values for α obtained from X-ray model fitting are due to small-scale structure in the H I column density, this structure must therefore exist where the average column density is in the range 2–4 × 10^{20} cm^{-2}. Such values are typical of intermediate and high galactic latitudes, and we have selected 20 regions at random with $|b| > 15°$ for the present study. Our observations are described below.

III. OBSERVATIONS AND DATA REDUCTION

Observations of high-latitude H I were made with the NRAO 43 m telescope, which has a beamwidth of 21′ at 21 cm. Spectra covered the LSR velocity range −264 to +264 km s^{-1}. The two linear polarizations were recorded separately, and independent parabolic baselines were removed. Data from the two polarizations were combined after determining that no significant differences were present. Calibration was performed with daily observations of the standard regions S6 and S8 (Williams 1973), and the observational variations were less than 1%.

Twenty 4° by 5° regions, at $|b| > 15°$, were selected at random. Table 1 gives the central direction for each region. Spectra were recorded every 20 s while the telescope was driven in a raster pattern along lines of constant declination separated by 0°.5. The telescope speed was typically 30′ or 90′ per minute of time. Most regions were mapped twice at the fast rate and once at the slow rate. The maps were offset from each other so that the spacing between observations, after combining all three maps, was 10′ in declination. The number of observations in each region was between 107 and 361, each with an rms noise per channel of less than 0.5 K.

Stray radiation was removed from each spectrum using a technique described by Lockman *et al.* (1984). Briefly, the many 43 m telescope spectra in each 4° by 5° region were combined to synthesize the profile that would have been observed by the 20 foot (6.1 m) horn antenna used in the recently completed Bell Telephone Laboratories (BTL) 21 cm survey (Stark *et al.* 1984). Because the BTL antenna has 92% of the response in the 2° main beam and almost all the response within 10°, it is relatively free from stray radiation problems. We thus interpreted any difference between the synthesized and the actual BTL profiles as stray radiation in the 43 m data, which we then subtracted from each of the 43 m spectra. The clean spectra were integrated to give total column densities. The velocity limits and average column densities are given in Table 1.

Tests indicate that residual sidelobe and baseline errors contribute an uncertainty of about 7 × 10^{18} cm^{-2} to individual measurements. System noise contributed a random error of 12 × 10^{18} cm^{-2}. Since we are trying to place upper limits on the true column density fluctuations, it is conservative to ignore these effects as is done in the analysis below.

IV. ANALYSIS

We examined the column density distribution within each 4° by 5° region for evidence of clumpiness, i.e., point-to-point column density variations. Because the two-component model of the soft X-ray background assumes that all the extragalactic component is produced beyond all the absorbing gas and the local component is completely unabsorbed, it is unimportant how the gas is distributed along the line of sight. We calculated apparent values for α_B and α_C from equation (1), where the sums are over the integrated column densities measured in one 4° by 5° region. This is called the "apparent" α because it includes the effects of beam smearing, as discussed below. The atomic cross sections were taken to be 1.75 × 10^{-20} cm^2 $atom^{-1}$ for the *B* band and 0.8 × 10^{-20} cm^2 $atom^{-1}$ for the *C* band (Burrows 1982). These values are slightly dependent on the assumed spectral form of the extragalactic X-ray component but cannot be changed significantly by any reasonable choice of spectrum which produces the observed *B* band to *C* band count ratio. It was verified that the values of apparent α agree when the column densities used are from only the slow scans in the map, only the fast scans, or all the scans. The apparent values for α_B and α_C are given in Table 1. The tabulated values are lower limits; random errors, which could exist due to radiometer noise or a varying (and therefore unremoved) stray radiation contribution, reduce the derived values for α. Even so, the apparent values of α calculated from

TABLE 1

SUMMARY OF 43 METER OBSERVATIONS

Region	l	b	Number of Points	Velocity Integration Limits		$\langle N_H \rangle$ (10^{20} cm^{-2})	α_B	α_C
1	24	39	147	−50	50	3.94	0.926	0.965
2	29	34	107	−100	100	4.56	0.960	0.981
3	32	−29	361	−60	60	3.75	0.942	0.970
4	34	24	361	−50	75	8.00	0.942	0.976
5	59	84	361	−100	100	0.98	0.934	0.970
6	61	40	361	−100	100	1.33	0.916	0.961
7	68	17	146	−150	50	6.35	0.888	0.942
8	77	39	362	−125	75	2.01	0.925	0.965
9	124	−31	160	−100	100	6.67	0.861	0.924
10	131	−30	361	−100	50	5.15	0.939	0.973
11	141	37	361	−100	50	3.08	0.858	0.913
12	150	33	361	−190	50	4.13	0.814	0.928
13	156	46	146	−125	50	1.36	0.872	0.935
14	160	50	147	−125	50	0.73	0.930	0.968
15	181	−58	361	−100	100	2.85	0.944	0.972
16	209	40	361	−75	75	3.68	0.961	0.982
17	221	16	361	−50	125	4.30	0.951	0.975
18	257	38	361	−75	75	5.53	0.869	0.925
19	264	71	361	−75	75	1.98	0.959	0.981
20	345	27	361	−75	50	8.60	0.931	0.962

the observations are not nearly as small as those required by the two-component model.

We must also consider the effect of beam smearing which tends to make the apparent value of α larger than its true value. A telescope with an infinitesimal beamwidth would measure the true value of α. This is the value relevant to the X-ray transmission if column density variations are the cause of the small values of the apparent absorption cross sections. With a finite beam, a distribution of clouds with large column density fluctuations would appear quite smooth (i.e., $\alpha \approx 1$) if the angular size of the clouds were sufficiently small. This effect is difficult to estimate analytically, and in order to determine the smallest angular cloud size for which the current observations can rule out the degree of clumping required by the two-component model, we have compared our data with a series of Monte Carlo simulations of observations of possible H I distributions.

The procedure is to construct many model "skies" by placing clouds randomly in three dimensions. The central column densities of the clouds are chosen so that the resulting column density fluctuations are exactly those required by the two-component model. We consider clouds with several radial density distributions, discussed in detail below, and find that the results are quite insensitive to the internal structure of the clouds. We have not included gradients in the average column density distribution in any of our simulations. While smooth gradients do reduce the true value of α, such large-scale structure is not hidden by beam smearing. The angular scale of the clouds was varied from model to model, and the Monte Carlo N_H distributions were convolved with the 43 m telescope beam profile in a pattern which duplicated the actual observations of a 4° by 5° region.

We use apparent α as a convenient statistic to determine whether a Monte Carlo H I distribution is inconsistent with our observations. We can determine, for each cloud geometry, the largest angular size which could be consistent with the data. Model skies are considered consistent with the data if the apparent α is not significantly smaller than the observed lower limits for α in Table 1. We have also used the apparent rms variation in the column densities as a discriminating statistic. It gives similar results but has the disadvantage, both in the simulations and the 43 m telescope data, of being a function of the average column density. In the data about one-third of this effect is due to radiometer noise; in the simulations it is only a consequence of Poisson statistics.

We first examined models with clouds of constant column density. The cloud thickness was chosen to be 1.3×10^{20} atoms cm^{-2}, which reduces the effective absorption cross sections to the values required by the two-component model (as discussed in § II). We examined other spherically symmetric clouds consistent with the two-component model, determining the required central column densities by trial and error. We define the radius of a cloud, R, to be the distance from the center to where the column density falls to 30% of the central column density.

We find that uniform spherical clouds with a central column density of 1.9×10^{20} atoms cm^{-2} produce $\alpha_B = 0.39$ and $\alpha_C = 0.61$, in reasonable agreement with the requirements of the two-component model. We have also considered clouds which have uniform density to radius r_c and a Gaussian density profile for $r > r_c$: $n(r) = n_0 \exp[-(r - r_c)^2/2\sigma^2]$. Defining R as above, clouds with $\sigma/R = 0.24$ and a central column density of 2.1×10^{20} cm^{-2} give $\alpha_B = 0.41$ and $\alpha_C = 0.62$. Clouds with $\sigma/R = 0.44$ and a central density of 2.3×10^{20} cm^{-2} give $\alpha_B = 0.43$ and $\alpha_C = 0.63$. Note that larger central column densities are required as clouds with softer edges are considered. Further it is clear that it is not possible to simultaneously match the requirements of the two-component model for both B and C bands with clouds of arbitrarily soft edges. Indeed, even the requirements of a single band cannot be met by arbitrarily soft-edged clouds. We plot in Figure 1 the column density profiles for the four cloud geometries discussed above if $R = 1$ pc. It is not clear whether clouds with softer edges are intrinsically more difficult to see than clouds with sharp edges; the soft edges are offset by the greater central column densities required to maintain the desired value of true α. Our simulations show that these two effects nearly cancel for all angular size scales.

We first describe model skies which are filled with clouds of constant angular size. Figures 2*a* and 2*b* show apparent α_B and α_C as a function of cloud size. The histograms in the upper right-hand corners summarize the distribution of apparent α_B and α_C actually observed with the 43 m telescope. The simulated observations are similar for the different cloud geometries, represented with the symbols indicated in Figure 1. The plotted error bars are the standard deviations from the multiple simulations run at each angular size and represent the scatter expected from a set of observations made at random locations on the sky. We compare the mean apparent α from the simulations to the mean apparent α from the 43 m telescope observations, for which the average apparent $\alpha_B = 0.92 \pm 0.01$ and the average apparent $\alpha_C = 0.96 \pm 0.005$. These errors are calculated with the assumption that the distribution is Gaussian. The 2 σ lower limits of the mean observed α are plotted as dashed lines in Figure 2. We find, in both bands, that if the cloud radius is greater than 14′, the simulated mean apparent α's are less than the mean α's actually observed. Thus, assuming that our errors in determining the mean observed α are Gaussian, the global structure necessary to explain the two-

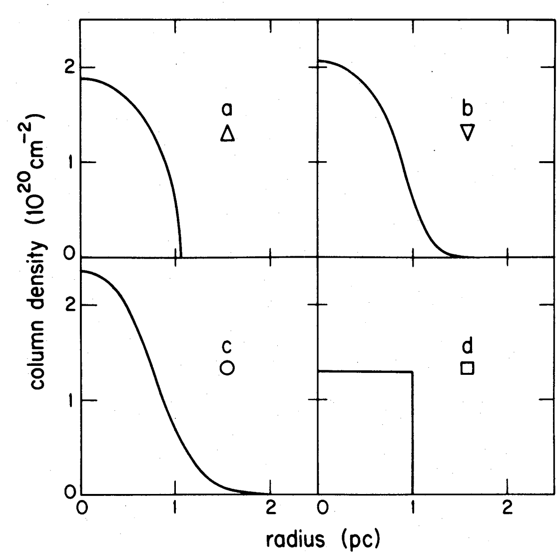

FIG. 1.—Column density as a function of radius for clouds consistent with the two-component model. These clouds have $R = 1.0$ pc. The symbols next to each profile are used in succeeding figures. Figure 1*a* shows uniform spherical clouds; 1*b*, clouds with $\sigma/R = 0.24$; 1*c*, clouds with $\sigma/R = 0.44$; and 1*d*, constant column density clouds.

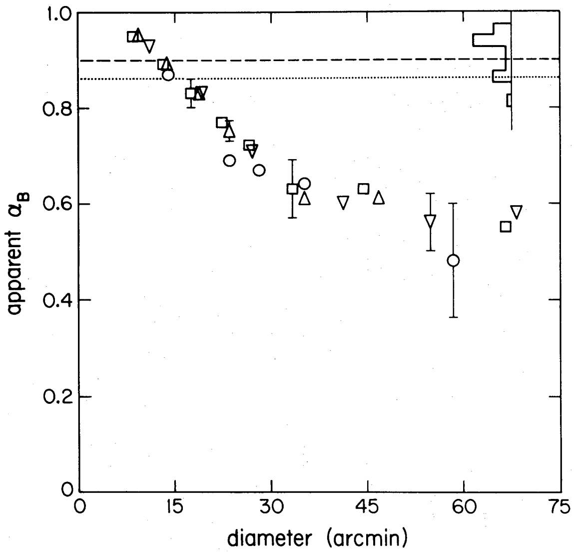

FIG. 2*a*

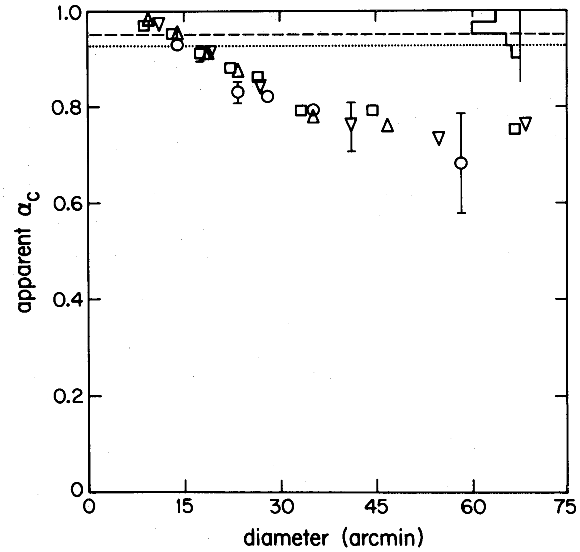

FIG. 2*b*

FIG. 2.—The apparent clumping parameter α_B (Fig. 2*a*) and α_C (Fig. 2*b*) for model skies with clouds of constant angular diameter. All models have the true fluctuations required by the two-component model. The symbols represent cloud geometries as indicated in Fig. 1. The histograms in the upper right summarize the 43 m telescope measurements of apparent α. The dashed lines are 2 σ lower limits to the mean observed mean α. Clouds consistent with the two-component model are ruled out by the 43 m observations for scales larger than 14′. The error bars are the mean standard deviation in the models and represent the scatter expected in many observations of skies with these properties.

component model does not exist on scales larger than 14′ at the 98% confidence level.

This comparison to the mean observed α's is appropriate since the required true α's are derived from global fits. However, at this angular scale, the simulated apparent α is a sharply falling function of cloud size. We have plotted dotted lines in Figure 2 that lie below 90% of the observed α's. For clouds larger than 25′, 90% of the observations are individually inconsistent with the simulations at the 98% (2 σ) confidence level. This implies that almost none of the sky has the column density fluctuations required by the two-component model on scales larger than 25′. The low value of α for $R = 60'$ is presumably a fluctuation due to the small number of simulations run at this size (only three in this case, while most other points are averages of ~ 10 runs).

More realistic H I distributions should have features with a wide range of angular scales. We have constructed three-dimensional models of the H I distribution by randomly placing clouds of constant linear diameter in three dimensions and projecting them onto the plane of the sky. Except as noted, the models assume a Gaussian scale height distribution of 135 pc (Falgarone and Lequeux 1973; Crovisier 1978, 1981). We also assume that no clouds are closer than 100 pc, as there is extensive evidence that the ISM is highly deficient in H I to approximately this distance in most directions (Sanders *et al.* 1977; Bohlin, Savage, and Drake 1978; Paresce 1983). We assume that the line of sight is at a galactic latitude of 30°. A relatively low latitude is chosen to maximize the effect of clouds having different sizes.

Figures 3*a* and 3*b* show the apparent α_B and α_C for skies filled with clouds of constant linear diameter. The lower horizontal scale is the cloud diameter in pc; the scales across the top give the maximum angular diameter and the diameter of a cloud at the scale height, which corresponds to a slant range of 270 pc for $b = 30°$. For all cloud geometries, clouds larger than 1.0 pc with central column densities as large as required by the two-component model produce mean apparent α's which are lower than the observed values at the 98% confidence level. The dashed and dotted lines in Figure 3 are identical to those in Figure 2. We have searched for a predictive relationship for apparent α as a function of the angular sizes of the nearest cloud and a cloud at the scale height. Though we found no simple relationship, we examined the sensitivity of the models to these two parameters. The effects are largest in cases where the slope of apparent α as a function of angular size is steep. For example, clouds with the profile of Figure 1*b* and size 1 pc in the simulations presented above, give apparent $\alpha_B = 0.79$ and $\alpha_C = 0.89$. If the scale height is doubled, to 270 pc, apparent α_B increases to 0.83, α_C to 0.91. A similar effect is observed if the scale height is held at 135 pc but the minimum distance is increased to 150 pc: α_B increases to 0.82, α_C to 0.90. However, a scale height of 270 pc and a minimum distance of 150 pc seem unreasonably large. We conclude that clouds consistent with the requirements of the two-component model are ruled out by the observations for linear sizes greater than 1 pc.

Another cloud geometry worth consideration is the core halo model suggested by McKee and Ostriker (1977) in their three-component model of the ISM. These authors suggest that clouds having cold dense cores ($n_c \approx 42$ cm^{-3}), warm diffuse mantles ($n_w \approx 0.25$ cm^{-3}), and an r^{-4} size distribution fill the ISM. (This size spectrum is so steep that almost all clouds have the minimum diameter, which McKee and Ostriker take as 1 pc.) The mantles are crucial to their model but contain too little gas to be significant X-ray absorbers or to contribute substantially to the average column density. We therefore treat the clouds as uniform spheres. Although clouds of the minimum diameter have nearly the same central column density as uniform spherical clouds which meet the requirements of the two-component model, the occasional presence of a larger cloud further reduces the true α's beyond the requirements of the absorption model. Lowering the density of the cloud cores to 20 cm^{-3} gives $\alpha_B = 0.37$ and $\alpha_C = 0.52$. We have

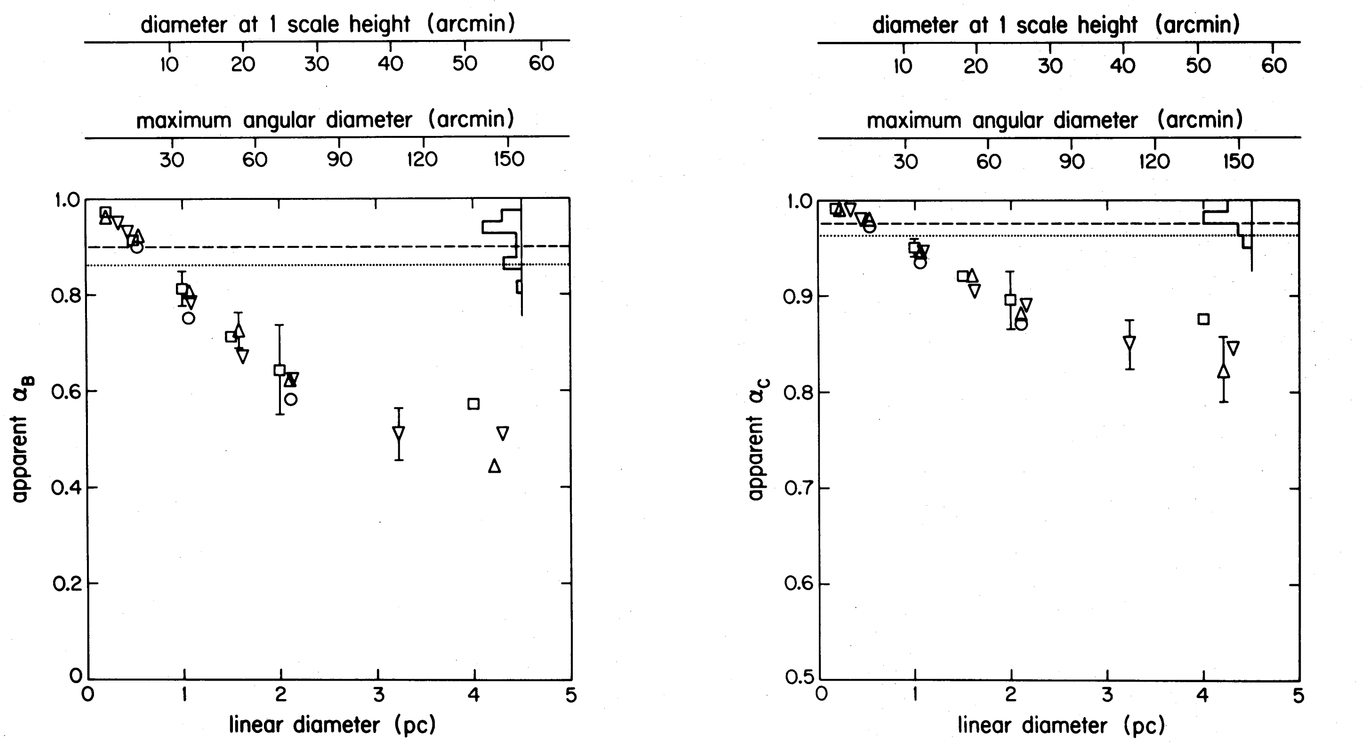

FIG. 3*a* FIG. 3*b*

FIG. 3.—The apparent clumping parameter α_B (Fig. 3*a*) and α_C (Fig. 3*b*) as a function of linear cloud diameter. These models assume a scale height of 135 pc, galactic latitude = 30°, a minimum distance of 100 pc, and have the column density fluctuations required by the two-component model. The symbols, dashed and dotted lines, and error bars have the same meaning as in Fig. 2. The lower scale gives the diameter of the cloud in pc. The upper scales give the maximum angular diameter and the diameter of a cloud at z = 135 pc. Under these conditions, clouds consistent with the two-component model and the observations cannot be larger than 1.0 pc in diameter.

run simulations with these clouds, assuming a scale height of 135 pc and a minimum distance of 100 pc. The apparent α's (apparent $\alpha_B = 0.55$, apparent $\alpha_C = 0.61$) for these models are well below the values derived from the 43 m observations. Thus, while the clouds postulated by McKee and Ostriker are close to the requirements of the two-component model, there is no evidence in the 43 m telescope observations that these clouds exist.

V. ANALYSIS OF OTHER WORK

Other observations exist which are sensitive to column density fluctuations with angular scales of several arc minutes and smaller. Payne (1980) used the Arecibo telescope to sample 21 cm emission brightness near extragalactic continuum sources. His maps cover regions about 10′ by 20′. Individual points are separated by 3′.8. We have selected the 12 maps from Payne's sample with 16 or more independent column densities and average column density less than 10 × 10^{20} atoms cm^{-2}.

We present in Table 2 the properties of each Arecibo map. In all regions α_B and α_C are near unity, which indicates that the gas distribution is smooth on scales of several arc minutes. These measurements ought to be sensitive to structures with angular scales between ~3′ and 20′. To evaluate the effects of beam smearing, these data were analyzed in exactly the same

TABLE 2

SUMMARY OF ARECIBO OBSERVATIONS

Region	l	b	Number of Points	Velocity Integration Limits	$\langle N_H \rangle$ (10^{20} cm^{-2})	α_B	α_C
3C 315	39	58	28	−30 30	4.58	0.998	0.999
PKS 1739	41	23	28	−30 50	5.06	0.991	0.995
3C 357	56	31	16	−30 30	3.18	0.991	0.996
3C 395	63	12	28	−30 50	8.31	0.975	0.987
3C 33	130	−49	28	−30 30	2.97	0.995	0.998
3C 47	137	−41	28	−30 30	4.44	0.988	0.994
3C 75	170	−45	16	−30 30	8.25	0.994	0.997
3C 200	194	33	16	−50 30	3.13	0.998	0.999
3C 192	198	26	16	−30 30	4.35	0.994	0.997
3C 227	229	42	21	−30 30	2.08	0.998	0.999
3C 270W	282	67	20	−50 30	1.60	0.999	0.999
PKS 1414	358	64	16	−30 30	1.86	0.998	0.999

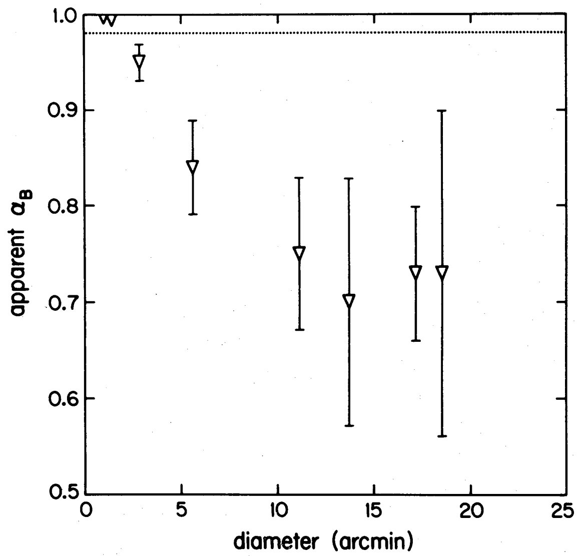

FIG. 4a

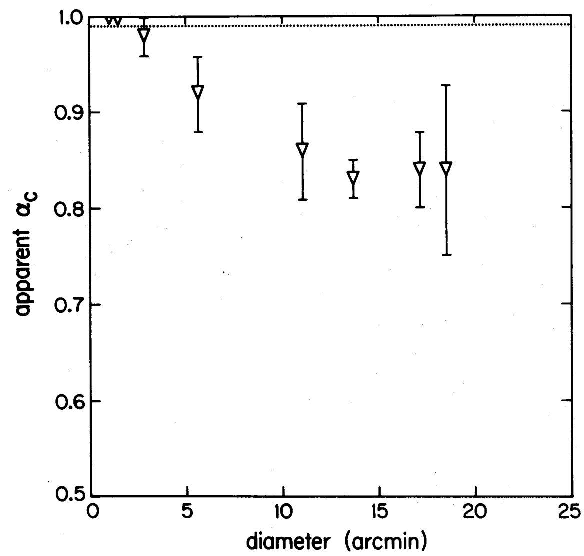

FIG. 4b

FIG. 4.—The apparent value of α_B (Fig. 4a) and α_C (Fig. 4b) for simulated Arecibo observations of H I distributions with the fluctuations required by the two-component model. These simulations assume clouds of constant angular diameter. The dotted lines (which fall below 90% of the observed α's) and the error bars have the same meaning as in Fig. 2. The dashed lines indicating the mean observed α's are omitted for clarity. The clouds required by the two-component models are not consistent with the Arecibo data for angular sizes larger than 2ʹ.5.

way as the 43 m telescope data. We examined model skies with clouds of small angular diameter and the column density fluctuations required by the two-component model. Payne's observations were simulated using Dickey's (1977) estimate of the Arecibo 21 cm beam profile. The mean apparent α's are smaller than those observed in Payne's maps for all cloud sizes from 2ʹ.5 to more than 20ʹ in models with clouds of constant angular diameter. The results are illustrated in Figures 4a and 4b. The scatter in the simulations increases for the larger cloud sizes since the simulated maps do not sample many clouds. The variation in the size of the error bars would, presumably, increase smoothly with cloud size if more simulations were run. The plotted points represent four to 12 simulations. The results for the Arecibo telescope are similar in form to the results derived for the 43 m telescope and rule out the column density variations required by the two-component model on the largest size scales still allowed by the 43 m results.

Finally, we consider an experiment which can detect fluctuations in the H I column density with an even smaller effective beamwidth. Dickey (1979) used the NRAO interferometer to examine differential 21 cm absorption spectra toward extragalactic double radio sources with component separations of 40ʺ to 220ʺ. With differential absorption features detected along only one (low-latitude) line of sight, Dickey concluded that absorption features of angular size $<3'$ are rare. Four of Dickey's sources have $|b| > 15°$ and are useful for limiting the amount of small-scale structure at intermediate latitudes. These measurements are sensitive to angular scales larger than the individual components of the radio sources and smaller than the separation between the sources. The upper limit is conservative as clouds with diameters larger than the separation could lie in front of one component and not the other. Properties of the four intermediate latitude sources are listed in Table 3. The separation of the two components is given by θ; the angular diameter of each component is given by d. The total H I column density observed in emission near these sources, derived from nearby spectra in the BTL Survey, is at least 6×10^{20} cm^{-2}. If this much gas is distributed in clouds of constant column density thick enough to satisfy the two-component model, there is an 85% chance that the difference in the number of clouds on two independent lines of sight is greater than or equal to 1. Thus if clouds consistent with the two-component model exist on an arc minute scale, there is a high probability that Dickey's experiment would measure column density differences equivalent to one or more clouds. To determine whether the experiment was sensitive enough to resolve the optical depth difference corresponding to one cloud, we estimate the maximum possible column density of undetected features which could exist on one line of sight and not the other from the rms fluctuations in Dickey's differential

TABLE 3

SUMMARY OF DOUBLE RADIO SOURCE EXPERIMENT

Source	l	b	θ (arcsec)	d (arcsec)	σ	$\tau(v)_{max}$	ΔN (10^{20} cm^{-2})	N_H (10^{20} cm^{-2})
3C 327	13	38	209	56	0.048	0.22	0.40	6
3C 353	21	20	220	62	0.013	1.20	0.29	9
3C 348	23	29	115	31	0.006	0.43	0.06	6
3C 109	182	−28	81	16	0.211	1.61	7.0	15

21 cm transmission spectra. We assume

$$\int (e^{-\tau_1(v)} - e^{-\tau_2(v)}) dv \leq \sigma_{\rm rms} n^{1/2} . \quad (4)$$

The limits of integration include any velocity range which corresponds to the width of an absorbing cloud; $\sigma_{\rm rms}$ is Dickey's observed rms fluctuation in the differential transmission spectra; n is the number of channels corresponding to the adopted upper limit for the velocity width of an absorbing cloud.

Since the data support the assumption that $\tau_1(v) \approx \tau_2(v)$, equation (4) becomes

$$\int e^{-\langle\tau(v)\rangle} (1 - e^{-\Delta\tau(v)}) dv \leq \sigma_{\rm rms} n^{1/2} , \quad (5)$$

where $\langle\tau(v)\rangle$ is the average optical depth toward the two components and $\Delta\tau(v)$ is the difference. The quantity $\Delta\tau(v)$ is small; we write

$$\int \Delta\tau dv \leq \sigma_{\rm rms} n^{1/2} \frac{1}{e^{-\langle\tau(v)\rangle_{\rm max}}} , \quad (6)$$

where $\langle\tau(v)\rangle_{\rm max}$ is the maximum of the average optical depth spectrum along the two closely spaced lines of sight. Taking the maximum optical depth is certainly an upper limit on the right-hand side of this equation. If we assume that an absorbing cloud has constant spin temperature T_s then

$$N \approx 1.82 \times 10^{18} T_s \int \Delta\tau dv \quad (7)$$

or

$$N \leq 1.82 \times 10^{18} T_s \sigma_{\rm rms} n^{1/2} \frac{1}{e^{-\langle\tau(v)\rangle_{\rm max}}} , \quad (8)$$

where N is the column density of a cloud which could exist along only one line of sight and still go undetected in Dickey's experiment. A cloud 3′ in diameter and 300 pc distant has a linear diameter of 0.26 pc. If it has density great enough to reduce $\sigma_{\rm eff}$ to the levels required by the two-component model and a pressure less than $P/k = 2 \times 10^4$ K cm^{-3}, the temperature must be less than 180 K. Since this limit on pressure is an order of magnitude higher than typical interstellar pressures (Spitzer 1978), we are confident that $T = 180$ K is a conservatively high upper limit. We take a maximum velocity width of 10 km s^{-1} for the absorbing features (see Table 2 of Payne, Salpeter, and Terzian 1982), which, for Dickey's experiment, implies $n^{1/2} = 2$. We now estimate from equation (8) the differential column density sensitivity of Dickey's four intermediate latitude measurements. The results are given in Table 3. Three of the paired lines of sight are sensitive to fluctuations in column density much smaller than the central density of one cloud with the properties required by the two-component model. These line of sight pairs are sensitive to column density differences between the pair of $\geq 4 \times 10^{19}$ atoms cm^{-2}. If the ISM is filled with clouds consistent with the two-component model and smaller than 3′, there is a 15% chance that any one paired line of sight would not sample different numbers of clouds, but the chance that three line of sight pairs would all produce a negative result is less than 1%, suggesting that clouds consistent with the absorption model must be smaller than the individual radio components or larger than 3′.

Finally, we must consider whether the required fluctuations could exist on angular scales less than the size of the individual components of the double radio sources. Table 3 shows the angular diameters of these sources, which are $\leq 1'$. Again assuming a maximum pressure of 2×10^4 K cm^{-3} and a distance of 300 pc, a spherical cloud 1′ in diameter and having a density consistent with the two-component model would have a temperature less than 30 K. Taking 10 km s^{-1} as an upper limit to the velocity width, we estimate the 21 cm optical depth of the cloud, and find τ_{21} cm $> \frac{1}{3}$. Once the optical depth of the cloud is this high, clumping reduces the apparent 21 cm column density as fast as it reduces the X-ray absorption cross sections. Therefore, clumping on scales of 1′ or less cannot explain the reduced apparent X-ray absorption cross sections as the clouds are becoming optically thick to 21 cm radiation as well. The double radio source experiment thus covers the smallest size scales relevant to the possible reduction of X-ray absorption cross sections due to clumping of interstellar gas.

VI. CONCLUSIONS

We have used the NRAO 43 m telescope to search for the neutral hydrogen column density variations that would be required by models in which a large fraction of the soft X-ray background originates outside the galactic disk and is absorbed by interstellar gas in the disk. Previous studies of the Hat Creek data have shown that if the required variations exist they must have angular scales smaller than about 1°. Models of possible H I distributions show that the required fluctuations are inconsistent with our observations unless the typical angular scales are smaller than 14′. Payne's Arecibo data rule out structure on angular scales from 20′ down to 2′.5. Dickey's analysis of 21 cm absorption toward extragalactic radio sources shows no evidence of the required variations on scales from 1′ to 3′. Pressure considerations make it unlikely that clouds smaller than 1′ have column densities as large as required by the two-component model unless they are so cold that they are also optically thick to 21 cm. Neutral hydrogen measurements thus show no evidence of the clumping of interstellar material required to explain the observed anti-correlation of soft X-ray intensity and H I column density as absorption of an extragalactic source of diffuse X-rays.

We point out that this conclusion in no way rules out the possible existence of a hot X-ray emitting corona. Even unclumped neutral material would still allow a small amount of additional flux from a corona source to be transmitted by minima in the H I distribution. This coronal contribution would be a minor fraction of the observed flux, and conclusions about the intrinsic luminosity of the corona are nearly the same as for the simple two-component model discussed in this paper. It is not currently possible, however, to make a convincing case of this as positive evidence for a hot corona.

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