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SMALL SCALE H I STRUCTURE AND THE  
SOFT X-RAY BACKGROUND

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ABSTRACT

The observed anticorrelation between diffuse soft X-ray flux and H I column density has been explained as absorption of soft X-rays produced in a hot galactic halo, assuming that the neutral interstellar material is sufficiently clumped to reduce the soft X-ray absorption cross section by a factor of two to three. We have extended a 21 cm emission line study of H I column density variations at intermediate and high galactic latitudes to 10' spatial resolution. The results confirm conclusions from preliminary work at coarser resolution, and in combination with other data appear to rule out the hypothesis that clumping of neutral interstellar matter on any angular scale significantly reduces X-ray absorption cross sections in the 0.13 - 0.28 keV energy range. We conclude therefore that the observed anticorrelation is not primarily a consequence of absorption of soft X-rays produced in a hot galactic halo.

Subject headings: interstellar: matter -- radio sources: 21 cm  
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Running Title: Small Scale H I Structure

## I. INTRODUCTION

An anticorrelation between the soft X-ray diffuse background intensity ( $E < 0.284$  keV) and the neutral hydrogen column density inferred from 21 cm measurements has been observed over much of the sky by independent experiments (McCammon et al. 1983 and references therein; Marshall and Clark 1984). An obvious explanation is that a substantial fraction of the soft X-ray background has a distant origin and is absorbed by galactic gas (Bowyer and Field 1969; Bunner et al. 1969; Marshall and Clark 1984). It has long been recognized, however, that there are quantitative difficulties with this interpretation; primarily, the observed X-ray variations are not as large as would be predicted from the measured H I column density variations. A possible resolution of this problem is in the idea that clumping of the absorbing gas has reduced its effective X-ray absorption cross section by, in effect, producing holes through the interstellar medium. For example, if all of the gas were in clouds of  $\sim 2 \times 10^{20}$  atoms  $\text{cm}^{-2}$  average thickness, soft X-rays would penetrate through the substantial gaps between the clouds and could produce results in quite good agreement with the observations in many parts of the sky. A similar amount of clumping is suggested by a recent three-dimensional model of the spatial variations of the soft X-ray background which embeds absorbing clouds at random within a hot X-ray emitting gas (Jakobsen and Kahn 1986).

This clumping hypothesis can in principle be tested directly by 21 cm emission measurements, for it is the fluctuations in total column density from one line of sight to another that determine the reduction

of average X-ray absorption. To rule out clumping, however, it must be shown that the required fluctuations do not exist on any angular scale smaller than the X-ray beam, and smoothing effects of the finite size of the radio beam must be taken into account. Jahoda et al. (1985, hereafter Paper I) studied column density fluctuations at 21' resolution and combined the results with an analysis of other observations and physical arguments to show that there seems to be no angular scale where the required amount of clumping exists. Here we extend the search to higher angular resolution and more directions to improve the confidence level of this conclusion and still find no evidence of the structure necessary to explain the small apparent absorption cross sections required by the distant origin models.

## II. OBSERVATIONS AND DATA REDUCTION

The 21 cm observations were made with the NRAO 91 m telescope during two three-week periods in 1984 June and August. The receiving system consisted of dual cooled FET amplifiers and a hybrid-mode feed that gave simultaneous linear polarizations. The system temperature was  $\sim 23$  K on the zenith. Most spectra cover  $260 \text{ km s}^{-1}$  with spectral resolution of  $1.4 \text{ km s}^{-1}$ ; several regions were observed with twice the velocity range and half the spectral resolution. The central velocity was chosen appropriately for each region. The 91 m telescope has an  $10'$  full width at half power beam at 21 cm.

Parabolic instrumental baselines were removed as described by Lockman, Jahoda, and McCammon (1986, hereafter LJM). The typical uncertainty in a derived column density, including random noise and

baseline uncertainties, was  $-6 \times 10^{18} \text{ cm}^{-2}$  for integration over a  $120 \text{ km s}^{-1}$  velocity range. The spectra have also been corrected for stray radiation using the procedure described in LJM for normalizing to the AT&T Bell Laboratories H I survey (Stark et al. 1986), which is assumed to be nearly free of stray radiation. This procedure requires mapping a sufficiently large area to synthesize the  $-2^\circ \times 3^\circ$  beam of the Crawford Hill horn reflector. In principle this could have been done directly with the 91 m telescope, but it was more efficient to map such a region around each selected area with the NRAO 43 m telescope and map only the much smaller 43 m main beam with the 91 m telescope. The requirement discussed in LJM that the map be completed in a short amount of time is really a limitation on the range of hour angles over which data can be collected, in order to ensure that the same far sidelobes of the antenna pattern remain above the horizon. This is readily satisfied by the transit observations made with the 91 m telescope, even though each map is assembled from scans made over a period of several days.

Sixty-four randomly selected  $2^\circ \times -1.4^\circ$  regions with  $|b| > 15^\circ$  were observed with the 91 m telescope. The locations of the individual regions are given in Jahoda (1986). All have declinations  $\geq -19^\circ$ , the physical limit of the telescope, and no regions with  $\delta > 65^\circ$  were selected due to the difficulty of making maps at high declination with a transit instrument. Observations of each region consisted of a series of drift scans  $2^\circ$  in right ascension separated by 5' in declination. All spectra were observed at transit with 20 s integrations; the individual spectra are therefore separated in right

ascension by  $5' \times \cos \delta$ . The typical rms noise per channel was 0.15 K. Maps covering the same regions but including enough area to synthesize the Crawford Hill main beam were obtained with the 43 m telescope in 1984 April. Each covers  $\pm 260 \text{ km s}^{-1}$  about the local standard of rest with spectral resolution of  $1.0 \text{ km s}^{-1}$ . The same receiver was used as for the 91 m observations.

### III. ANALYSIS

The spatial distributions of X-ray intensity in the B band (0.13 - 0.188 keV) and C band (0.16 - 0.284 keV) of the Wisconsin sky survey (McCammon et al. 1983) have been analyzed in terms of a two-component model which includes a local X-ray source (assumed isotropic and unabsorbed) and a distant X-ray source absorbed by  $\exp(-\sigma_{\text{eff}} \langle N_{\text{H}} \rangle)$ , where  $\langle N_{\text{H}} \rangle$  is the average column density in the X-ray detector field of view and  $\sigma_{\text{eff}}$  is an effective absorption cross section which is a free parameter of the model but has the same value in all directions. The derived effective cross sections are smaller than expected for photoelectric absorption in the interstellar medium with normal (10%) helium abundance by a factor of 0.43 for the B band and 0.67 for the C band. Marshall and Clark (1984) analyzed their C band data in terms of the same two-component model, and find an effective X-ray absorption cross section of 0.53 times the calculated value. This is a slightly larger reduction than our result, but their C band has a somewhat lower effective energy than the McCammon et al. (1983) C band, so the agreement of these independent data sets is quite reasonable.

One explanation of the small effective cross sections derived from the X-ray model fitting is that clumping of the interstellar material causes column density fluctuations across the X-ray detector beam which reduce the X-ray absorption. The ratio  $\alpha$  between the effective cross section and the calculated cross section is then given by

$$\alpha = \frac{\sigma_{\text{eff}}}{\sigma} = \frac{-\ln\left(\frac{1}{n} \sum_i \exp(-\sigma(N_H)_i)\right)}{\sigma \frac{1}{n} \sum_i (N_H)_i} \quad (1)$$

where the sums are in principle over all lines of sight in the X-ray detector field of view but can be approximated by any unbiased sample of  $n$  lines of sight, and  $\sigma$  is the theoretical cross section. If the  $N_H$  fluctuations are produced by a random distribution of clouds, then  $\alpha$  depends only on the column densities of the individual clouds and is independent of the total column density. The same cloud size which gives a reduction factor  $\alpha_B$  for the B band of 0.43 predicts a C band reduction  $\alpha_C$  of 0.64, so the clumping hypothesis meets the requirements of the X-ray data, interpreted in the context of distant origin models, rather well.

We followed the analysis procedure of Paper I to determine the range of clumping size scales which could be consistent with our 21 cm observations while producing sufficient column density fluctuations to reduce  $\alpha$  to the required levels. A complete description of the procedure is given in that paper; an outline is presented here. We created Monte Carlo models of possible three-dimensional gas distributions which have intrinsic column density fluctuations that

reduce  $\alpha_B$  to  $-0.44$  and  $\alpha_C$  to  $-0.62$ . Several series of models, each with clouds of a particular diameter, were run to cover the range of size scales of interest. These models were "observed" with the measured beam pattern in faithful simulations of our observing program. We used the "apparent  $\alpha$ " as a statistic to compare the observations with the models. The apparent  $\alpha$  is evaluated from equation 1 using the beam averaged column densities from the 91 m observations or from the simulations in place of the individual  $(N_H)_i$  values in equation 1, which refer to column densities for single lines of sight. The apparent  $\alpha$  will always be larger (indicating a smoother distribution) than the true  $\alpha$  due to the finite size of the 91 m telescope beam. The apparent  $\alpha$  is, of course, not the only statistic which could be used to compare observations and models, but it has the convenient property that if all of the gas is contained in randomly distributed clouds of constant size, it is independent of the total column density. A given cloud size is considered inconsistent with the observations if the distribution of apparent  $\alpha$ 's calculated from the series of models with that cloud diameter is significantly different from the observed distribution of apparent  $\alpha$ 's for the random selection of intermediate and high latitude regions surveyed.

Figures 1a and 1b present the comparison between observations and models (and are similar to figures 3a and 3b of Paper I). The values of apparent  $\alpha$  from the observations are summarized by the histograms in the upper right. The solid lines are the  $2\sigma$  lower limits to the mean of the observed apparent  $\alpha$ 's, while the dashed lines fall below 90% of the observed values. Each cross represents the apparent  $\alpha$  from an



individual model. The models assume the gas to be entirely contained in uniform spherical clouds which are randomly distributed with a 135 pc scale height. No clouds are closer than 100 pc, the line of sight is at  $b = 30^\circ$ , and all clouds have the same linear dimensions for a given model. We have not run simulations for clouds with other geometries: one of the results of Paper I is that the apparent  $\alpha$ 's are insensitive to cloud geometry and density profile when the central column density is adjusted to give the required reduction in average X-ray absorption. The lower horizontal scale shows the linear diameter of the clouds in each model and the upper scales show the angular diameters of a typical cloud (at the scale height and thus 270 pc distant) and of the largest clouds (100 pc distant). The horizontal arrows mark the average true  $\alpha$  of all the simulations. There is a small scatter in these values due to the random nature of the models. The simulations show that the required clumping would have been detected easily if its typical angular scale were larger than about  $5'$ .

#### IV. CONCLUSIONS

Comparison of data from the 43 m and 91 m telescopes shows that very little additional structure is resolved in the high latitude neutral hydrogen distribution in going from  $21'$  angular resolution to  $10'$ . Structure in this angular range is completely dominated by large-scale gradients as a source of column density variations across the  $6^\circ$  field of view of an X-ray detector. This observation reinforces the general impression that the magnitude of column density fluctuations decreases monotonically with angular scale at intermediate

and high galactic latitudes, at least down to the resolution limit of the 91 m telescope. This trend would have to be dramatically reversed on yet smaller scales to allow the rather extreme column density fluctuations which would provide the small apparent X-ray absorption cross sections required by distant origin models of the soft X-ray background. Based on the large number of high latitude directions sampled by the 91 m observations, we can put an upper limit of 5' on the typical angular scale of any such structure. However, other experiments and physical arguments discussed in Paper I are inconsistent with the existence of the required column density fluctuations on any angular scale smaller than  $\sim 10'$ .

We conclude that the small values derived for apparent cross sections in distant origin models of the soft X-ray background cannot be explained by clumping of interstellar material. As noted in Paper I this is not an argument against the existence a hot galactic halo. However, any such halo could contribute only a small fraction of the observed soft X-ray background.

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FIGURE CAPTION

Fig. 1--The apparent clumping parameter  $\alpha_B$  (fig. 1a) and  $\alpha_C$  (fig. 1b) from the data and the models. The histograms in the upper right summarize the 91 m telescope measurements of apparent  $\alpha$  for randomly selected areas at intermediate and high galactic latitudes. The solid lines are  $2\sigma$  lower limits to the mean observed apparent  $\alpha$ . The dashed line falls below 90% of the observed values. Each cross represents the apparent  $\alpha$  from an independent Monte Carlo model plotted as a function of cloud diameter. These models assume a scale height of 135 pc, galactic latitude of  $30^\circ$ , no clouds within 100 pc, and have the column density variations required by distant origin models of the soft X-ray background. The horizontal arrows show the true  $\alpha$  used for all the Monte Carlo simulations. The models are inconsistent with the observations for cloud diameters larger than  $\sim 0.4$  pc.

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