THE ASTROPHYSICAL JOURNAL, 311:L57–L61, 1986 December 15

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

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Received 1986 May 27; accepted 1986 September 22

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 2–3. 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, on *any* angular scale, the hypothesis that clumping of neutral interstellar matter 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 radiation — X-rays: general

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 emission 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 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 recent three-dimensional model for the soft X-ray background which embeds absorbing clouds at random within a hot X-ray emitting gas (Jakobsen and Kahn 1986) requires a similar amount of clumping if the scale height of the hot gas is to be much larger than the scale height of the absorbing gas.

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 the required amount of clumping does not exist on any angular scale. 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 3 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 ~ 23 K on the zenith. Most spectra cover 260 km s^{-1} with spectral resolution of 1.4 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 a 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 $\sim 6 \times 10^{18}$ cm^{-2} for integration over a 120 km s^{-1} velocity range. The

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[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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° × 3° 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 $2° \times \sim 1.°4$ regions with $|b| > 15°$ were observed with the 91 m telescope. The locations of the individual regions are given in Jahoda (1986). All have declinations $\geq -19°$, the physical limit of the telescope, and no regions with $\delta > 65°$ were selected due to the awkwardness of making maps at high declination with a transit instrument. Observations of each region consisted of a series of drift scans 2° 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 ± 260 km s^{-1} about the local standard of rest with spectral resolution of 1.0 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 $\exp(-\sigma_{\rm eff}\langle N_{\rm H}\rangle)$, where $\langle N_{\rm H}\rangle$ is the average column density in the X-ray detector field of view (as determined from 21 cm emission measurements) and $\sigma_{\rm eff}$ 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.* 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 α between the effective cross section and the calculated cross section is then given by

$$\alpha = \frac{\sigma_{\rm eff}}{\sigma} = \frac{-\ln\left[(1/n)\Sigma_i \exp - \sigma(N_{\rm H})_i\right]}{\sigma(1/n)\Sigma_i(N_{\rm H})_i}, \qquad (1)$$

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 σ is the theoretical cross section. If the $N_{\rm H}$ fluctuations are produced by a random distribution of clouds, then α 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 α_B for the B band of 0.43 predicts a C band reduction α_C of 0.62, 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 α 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 α_B to ~ 0.44 and α_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 α" as a statistic to compare the observations with the models. The apparent α 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 $(N_{\rm H})_i$ values in equation (1), which refer to column densities for single lines of sight. The apparent α will always be larger (indicating a smoother distribution) than the true α due to the finite size of the 91 m telescope beam. The apparent α 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 α's calculated from the series of models with that cloud diameter is significantly different from the observed distribution of apparent α's for the random selection of intermediate- and high-latitude regions surveyed.

Figures 1*a* and 1*b* present the comparison between observations and models (and are similar to Figs. 3*a* and 3*b* of Paper I). The values of apparent α from the observations are summarized by the histograms in the upper right. The solid lines are the 2σ lower limits to the mean of the observed apparent α's, while the dashed lines fall below 90% of the observed values. Each cross represents the apparent α 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 $b = 30°$, 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 α'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 α 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. ADDITIONAL CONSTRAINTS

a) H I *Opacity*, H_2 *and* H^+

It is important to keep in mind that the effective absorption cross section per H I atom required by "distant-origin" models of the soft X-ray background was determined using H I column densities derived from 21 cm emission measurements with the assumption that the gas is optically thin. Total X-ray cross sections were calculated using the normal relative abundance of He; only H and He absorb significantly at the X-ray energies of interest. Additional undetected material (H_2, H^+, or optically thick H I) can only *add* to the cross section per H I atom and, "distant-origin" models would thus require even more clumping *of the detected* H I to compensate for it. Although only H^+ is likely to be important at high latitudes, the presence of any of these other species can only make the effective cross section problems worse. (H I opacity in fact places a lower limit on the linear size of cloud which needs to be considered here: once the density is high enough that the

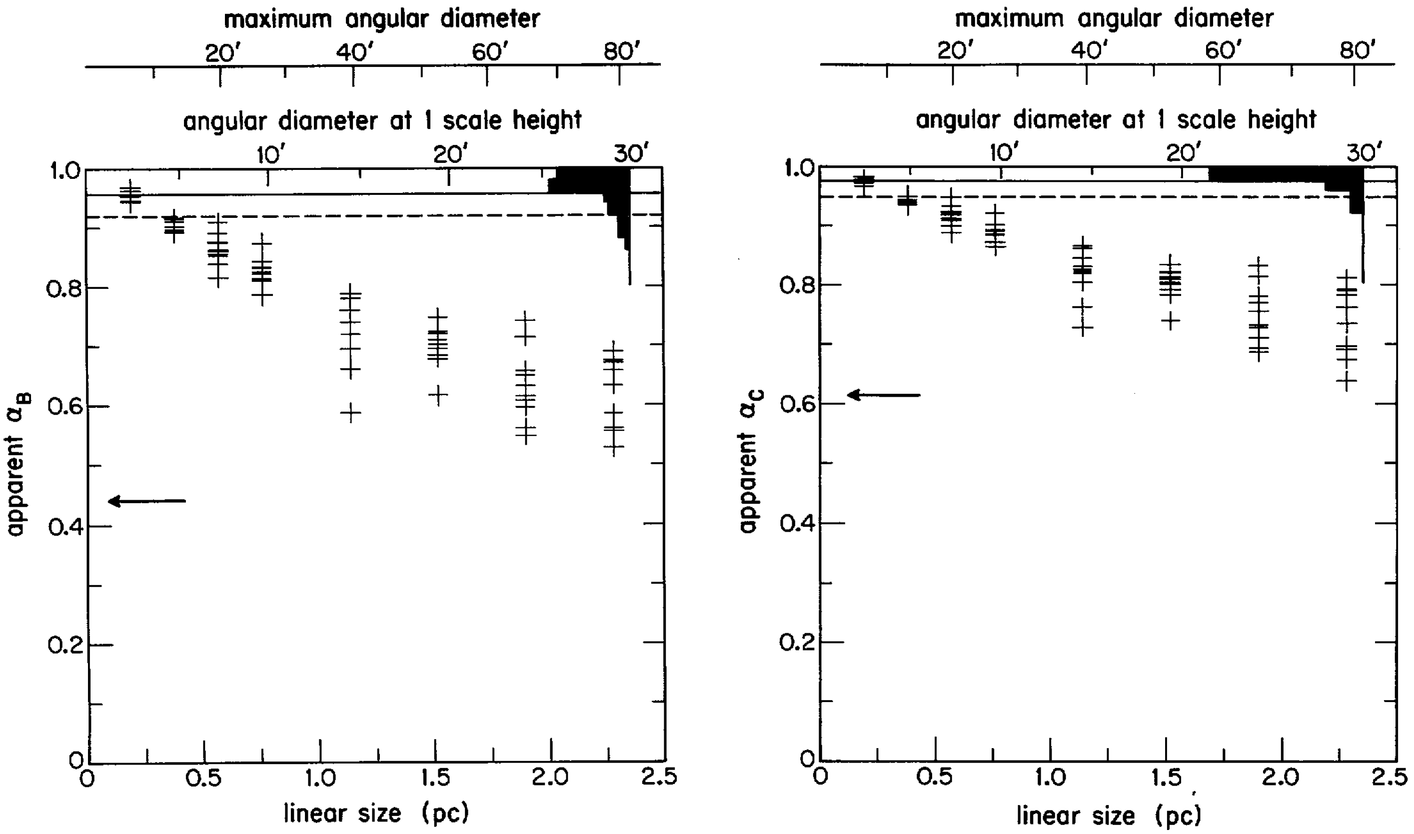

FIG. 1*a* FIG. 1*b*

FIG. 1.—The apparent clumping parameter α_B (Fig. 1*a*) and α_C (Fig. 1*b*) from the data and the models. The histograms in the upper right summarize the 91 m telescope measurements of apparent α for randomly selected areas at intermediate and high galactic latitudes. The solid lines are 2 σ lower limits to the mean observed apparent α. The dashed line falls below 90% of the observed values. Each cross represents the apparent α 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°, 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 α used for all the Monte Carlo simulations. The models are inconsistent with the observations for cloud diameters larger than ~ 0.4 pc.

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cloud becomes optically thick to 21 cm, the gas in its interior that is "hidden" to the X-rays is also hidden to 21 cm emission measurements, and it ceases to help in reducing the apparent X-ray cross section.)

b) *Higher Angular Resolution Studies*

Our data rule out significant clumping on angular scales > 5′. Could the required fluctuations in column density be on smaller angular scales? We emphasize that the column density fluctuations we are looking for are not subtle. The apparent cross sections required by the X-ray absorption models are determined mainly in regions where the apparent optical depth is near unity, or $\sim 2 \times 10^{20}$ H I cm^{-2}. At this total column density, the required rms fluctuations are nearly ±100%. A random distribution of clouds with individual column densities $\sim 1.5 \times 10^{20}$ cm^{-2} will produce such fluctuations, but only if more than two-thirds of all interstellar material is contained in these clouds. The ~ 100% *downward* fluctuations are the important quantity, and the mere existence of some 1.5×10^{20} cm^{-2} clouds is not sufficient to produce them. Paper I discusses evidence that the total column density of H I is smooth on all scales, and more recent observations reinforce this conclusion.

Radio measurements show no evidence that *a large fraction* of the ISM is contained in very small clouds. Although high angular resolution observations made specifically to investigate this possibility have detected some structure in cool H I on all angular scales, the fluctuations are always a *small fraction of the total column density*. The same H I absorption statistics are found toward pulsars (essentially point sources) and toward extended (from arc seconds to > 3′) radio sources, implying that the solid angle filling factor of the absorbing gas is essentially unity (Dickey *et al.* 1981; Payne, Salpeter, and Terzian 1983). Likewise, observations of 3C 273 at 2″.8 resolution led Liszt, Dickey, and Greisen (1982) to conclude that "the gross properties of interstellar clouds are distributed smoothly in space but that high-sensitivity observations can reveal slight variations (2%) which have very small scales." More recently, similar observations toward three other extragalactic radio sources prompted Greisen and Liszt (1986) to "infer that the absorbing material has a large covering factor, i.e., that the projected surface area of that material does not have large gaps through which portions of the beam may penetrate without encountering absorption."

The absorption studies referenced above give information on only the cooler components of interstellar H I. Even less small-scale structure would be expected in warm gas. This has been confirmed by Kalberla, Schwarz, and Goss (1985), who combined emission and absorption observations to cover angular scales from ~ 1′ to > 10′, and conclude that "most [80%] of the observed H I gas is extended on scales > 10′." This is also apparent in an analysis of 21 cm emission data collected at intermediate and high galactic latitudes by Payne (Paper I), which shows that fluctuations in the total column density as measured with 3′.8 resolution are typically < 5% on angular scales < 20′. Finally, the fact that an identical total H I column density (to within the ~ 20% instrumental errors) is measured toward distant, high-latitude stars whether one uses 21 cm emission profiles obtained with a 21′ beam or Lyman-α absorption measurements from the star itself, makes it extremely unlikely that high-latitude H I is significantly clumped (Lockman, Hobbs, and Shull 1986).

V. 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° field of view of an X-ray detector. These observations reinforce 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 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. There is no evidence that this is the case: as discussed in § IV*b*, H I *absorption* studies sensitive to fluctuations on scales of 5′ and smaller, uniformly find instead that the trend toward smoother distribution of total H I continues down to the smallest physically meaningful angular scales (see also Payne, Salpeter, and Terzian 1983). The presence of other species (H_2, H^+), or of H I optically thick at 21 cm, can only add to the effective X-ray cross section per detected H I atom, making the problems with distant-origin models even worse.

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 of a hot galactic halo. However, any such halo can contribute only a small fraction of the observed soft X-ray background.

This research was supported in part by the National Aeronautics and Space Administration under grant NAG 5-629. We are grateful for the use of the Midwest Astronomical Data Reduction and Analysis Facility (MADRAF).

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