Accurate galactic N(H) values towards quasars and AGN

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ACCURATE GALACTIC $N_H$ VALUES TOWARDS QUASARS AND AGN

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ABSTRACT

We have measured integrated Galactic 21 cm column densities toward ~174 quasars and active galactic nuclei using the NRAO 140 ft telescope at Green Bank. These data have been corrected for stray radiation with the technique of Lockman et al. (1986). The 21 arcmin beam size of the 140 ft is small enough to minimize the uncertainty in $N_H$ due to angular variations in the $H_1$ of the Galaxy at high latitudes. The resulting column densities are accurate to $\sim 1 \times 10^{20}$ atoms cm$^{-2}$ or $\sim 5\%$, whichever error is larger. Opacity uncertainties dominate the errors above $N_H \sim 4 \times 10^{20}$ atoms cm$^{-2}$.

I. THE NEED FOR ACCURATE $N_H$ VALUES

The extension of sensitive extragalactic x-ray measurements to the band below the 0.28 keV carbon edge (the “C band,” McCammon et al. 1983) has made it important to determine accurately the opacity of the interstellar medium of our own galaxy at these energies. Interpretation of spectral results from the Einstein IPC (Imaging Proportional Counter, Gorenstein et al. 1981) and the EXOSAT CMA (Channel Multiplier Array, Taylor et al. 1981) depends critically on a knowledge of the Galactic $N_H$. The inferred properties of the recently discovered “ultrasoft excesses” in the x-ray spectra of quasars and active galactic nuclei (AGN) are particularly sensitive to this value (Wilkes and Elvis 1987; Branduardi et al. 1987; Giommi and Tagliaferri 1987).

Most x-ray astronomers currently use the unpublished but widely circulated “Bell Labs” survey (Stark et al. 1984) of 21 cm $H_1$ emission to determine the column densities of interstellar material toward extragalactic sources. This survey is superior to previous all-sky $H_1$ surveys because the telescope’s unblocked aperture makes it almost free of “stray radiation” entering the signal from distant sidelobes. The small size of the antenna, however, has the disadvantage that the angular resolution is poor, typically $\sim 2' \times 3'$. Small-scale structure in the $H_1$ distribution on the sky is thus liable to introduce errors in the column toward any particular line of sight. Elvis et al. (1986, Appendix B) estimated that the 90% errors introduced by small-scale structure were $\pm 1 \times 10^{20}$ atoms cm$^{-2}$. For a typical high Galactic latitude position with $N_H \sim 3 \times 10^{20}$ atoms cm$^{-2}$, this uncertainty of $1 \times 10^{20}$ atoms cm$^{-2}$ in $N_H$ leads to a factor-of-2.4 uncertainty in the intrinsic x-ray flux density of a source at 0.2 keV. Column densities more accurate than the Bell Labs survey provides are thus clearly needed.

A method for achieving high-angular-resolution $H_1$ measurements free from stray radiation has recently been developed for the Green Bank 140 ft telescope (Lockman, Jahoda, and McCammon 1986, Appendix A). We have used this technique to produce accurate $H_1$ column densities toward a large number of quasars and AGN that are bright and well-observed x-ray sources. We present these column densities here. We also analyze the results to provide an assessment of the remaining errors and to determine more carefully the uncertainties involved in using the Bell Labs survey values when no more accurate measurement is available.

II. OBSERVATIONS

The sample of objects includes a wide selection of x-ray-observed AGN and quasars. It includes, so far as they were observable from Green Bank (i.e., declination $\geq -40\%$), all the quasars with Einstein IPC spectra in Wilkes and Elvis (1987), all the BL Lac objects with Einstein IPC spectra in Madejski (1985), a substantial number of other Einstein observed quasars for which IPC x-ray “colors” are available (Brunner et al. 1988), all of the members of the complete hard (2–10 keV) x-ray-selected “Piccinotti” sample of AGN (Piccinotti et al. 1982), and a selection of the AGN detected by the Medium Energy instrument on EXOSAT (Sternberg et al. 1986). In addition, we mapped the accessible Einstein Deep Survey regions (Giacconi et al. 1979), the “Braccesi” survey region covered by Marshall et al. (1984), SA 57, and the North Ecliptic Pole regions that will be observed in depth by ROSAT. The maps for these extended regions will be presented separately.

The observing technique was as detailed by Lockman et al. (1986, Appendix A). Briefly, the 140 ft telescope is used to map out the beam covered by the Bell Labs observation that was centered closest to the position of each AGN. The 140 ft data are then convolved with the beam profile of the Bell antenna to give the 21 cm spectrum that the 140 ft would observe if it had the same beam shape as the Bell antenna, i.e., including the stray radiation seen by the 140 ft at this position. This spectrum is dependent on the altitude and azimuth of the telescope as well as on the celestial position. The difference between the Bell spectrum and the convolved 140 ft spectrum is then the stray radiation seen by the 140 ft at that position. This is then subtracted from the 140 ft spectrum taken at the precise position of the active galactic nucleus.
In practice, two independent spectra were taken at each AGN position. Total integration times were 2–6 min. Because of the low system temperature (18 K at zenith), these integration times are sufficient to make the uncertainty in \( N_H \) due to noise negligible. An observation of particularly low signal-to-noise is shown in Fig. 1. Each AGN position was observed both immediately before and after the Bell beam was mapped and the results averaged, to minimize time-dependent effects. Remaining errors in the observation are primarily due to uncertainties in the baseline (Lockman et al. 1986) and amount to \( \sim 2 \times 10^{18} \) atoms cm\(^{-2}\). The amount of the stray radiation removed was equivalent to \( \text{H}\,\text{i} \) columns of a few \( \times 10^{19} \) atoms cm\(^{-2}\), or \( \sim 15\% \) for typical values of \( N_H \). Figure 2 shows an example of a particularly large stray-radiation spectrum compared with the observed 140 ft spectrum. There is uncertainty in the stray-radiation correction at a level of a few times \( 10^{18} \) atoms cm\(^{-2}\), and the form of the uncertainty is not well determined.

To derive an integral \( N_H \) measurement from the observed spectrum requires a correction for the opacity \( \tau \) of the gas. Although at high Galactic latitudes this correction is generally small, it is sometimes dominant. The correction is intrinsically uncertain. The observed spectrum is made up of contributions from different clouds in the interstellar medium, which generally have a wide range of temperatures and optical depths and many possible geometric arrangements (see discussions in Dickey and Benson 1982; Lockman and Dickey 1989). The distribution of these clouds cannot be derived.

**Fig. 1.** Low signal-to-noise 21 cm spectrum from the NRAO 140 ft. The \( N_H \) in this spectrum (corrected for stray radiation) is \( 1.23 \times 10^{20} \) atoms cm\(^{-2}\)).

**Fig. 2.** Sample of the stray-radiation spectrum (lower line) removed from the observed data (upper line).
from a 21 cm spectrum. The size of the uncertainty can be estimated using the peak observed brightness temperature in the spectrum $T_{\text{peak}}$

$$T_{\text{peak}} = T_{\text{spin}} (1 - e^{-r})$$

if we assume that the emission arises from gas of a fixed kinetic temperature (called the spin temperature $T_{\text{spin}}$ for historical reasons). If $T_{\text{peak}}$ is small, then $r$ is always small for reasonable values of $T_{\text{spin}}$, but for larger $T_{\text{peak}}$, $r$ is more likely to be significant and one must make an opacity correction. Figure 3 shows the uncertainty in $N_{\text{H}}$ due to opacity corrections, $\Delta N_{\text{H}} (T_{\text{spin}})$, plotted against $T_{\text{peak}}$. $\Delta N_{\text{H}} (T_{\text{spin}})$ was calculated using $T_{\text{spin}}$ values of $10^4$ K and 125 K as extreme cases. A best fit to Fig. 3 gives

$$\Delta N_{\text{H}} (T_{\text{spin}}) = (0.073 \pm 0.005) T_{\text{peak}} - (0.063 \pm 0.007) \times 10^4 \text{ atoms cm}^{-2}.$$  

This expression, or Fig. 3, can be used to estimate the opacity-correction uncertainty in our $N_{\text{H}}$ measurements.

The best-estimate column densities are given in Table I. Values of $N_{\text{H}}$ are given for an assumed effective spin temperature of 250 K, which is a good approximation to that of the interstellar H I (Dickey, private communication; see also Dickey 1988). When the H I signal is brighter than several tens of Kelvins, the Bell Labs survey data, and hence our

![Fig. 3. Uncertainty due to opacity uncertainties ($N_{\text{H}}$, 10,000 K) - $N_{\text{H}}$ (125 K)](image_url)
techniques for removing stray radiation, become unreliable. However, the brightness of the H I means also that stray radiation will be a relatively unimportant component of the total \( N_H \) and the "uncorrected" 140 ft spectra are thus fairly accurate. Sources so affected are flagged in Table I; the uncertainty in their \( N_H \) is dominated by the uncertain opacity correction. We also tabulate the peak brightness temperature (\( T_{\text{peak}} \)). The dominant error in the tabulated column density may be due to either the baseline noise referred to above or to the uncertainty due to the opacity correction. Figure 4 shows how the uncertainty in \( N_H \) due to \( T_{\text{peak}} \), \( \Delta N_H (T_{\text{peak}}) \) dominates above the measurement errors of \( \approx 10^{19} \) atoms \( \text{cm}^{-2} \) (dashed line) for \( N_H > 4 \times 10^{20} \) atoms \( \text{cm}^{-2} \). If the area under Galactic H I profiles could always be measured to \( \pm 2\% \), then opacity-correction uncertainties would dominate at all values of \( N_H \).

Figures 5(a) and 5(b) compare the optically thin 140 ft and Bell values of \( N_H \) as both a ratio and a difference as a function of \( N_H \) (140 ft). The ratio of 140 ft/Bell stays constant with \( N_H \), while the difference seems to grow slightly. This suggests that small-scale structure is a constant fraction of the total. That is, at high latitudes the Galactic \( N_H \) in a 21' field is equal to that in the 3' \( \times \) 2' Bell fields with a 1\( \sigma \) uncertainty of 11% on average.

### III. CONCLUSIONS

The values of \( N_H \) tabulated here have typical uncertainties of \( \approx 10^{19} \) atoms \( \text{cm}^{-2} \) and so are about ten times more accurate than column densities derived from the Bell Labs survey alone. It is worth noting here that for the purposes of investigating small amounts of x-ray absorption it is the col-

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**Table I. (continued)**

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<th>Object</th>
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| MKN 241  | 11 01 40.5 | 38 28 42 | 1.45 | 1.5 | \( \Delta N_H \) (dashed line) for \( N_H > 4 \times 10^{20} \) atoms \( \text{cm}^{-2} \). If the area under Galactic H I profiles could always be measured to \( \pm 2\% \), then opacity-correction uncertainties would dominate at all values of \( N_H \).

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Explanation:

1. Bright H I spectrum. Was not corrected for stray radiation (see text).
2. Bell Labs survey was extrapolated to correct this spectrum. Error may be larger than normal.

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umn density due to hydrogen and helium alone that contributes to the photoelectric cross section in the C band below 0.28 keV (Morrison and McCammon 1983). Hydrogen in any form other than atomic appears to be uncommon at high Galactic latitudes (Blitz, Magnani, and Mundy 1984) so that the 21 cm data give an unusually direct and clean means of determining the column that must absorb x rays.

The extreme x-ray–ultraviolet telescopes on ROSAT (Pye 1984) and EUVE (Bowyer 1987) can only detect extragalactic sources if they lie in directions of unusually small Galactic column density. There are two AGN in Table I with $N_H$ below $0.9 \times 10^{20}$ atoms cm$^{-2}$ and seven with $N_H$ below $1.1 \times 10^{20}$ atoms cm$^{-2}$. These low $N_H$ AGN will make good targets for the extreme x-ray–ultraviolet telescopes. Our nearly 200 AGN form an essentially random sample of the high-latitude sky. We can estimate then that roughly 1% of the sky has column densities of $0.9 \times 10^{20}$ atoms cm$^{-2}$ or less.

The need for more accurate column densities will rise rapidly with the many soft-x-ray sources that are expected to be discovered with the soft-x-ray sky-survey satellite ROSAT (Trümper 1984, due for launch in February 1990). The effects of uncertain Galactic $N_H$ can be important to log $N$–log $S$ studies and hence to questions of quasar evolution and the origin of the x-ray background (Zamorani et al. 1988). An all-sky survey of Galactic $N_H$ with a beam size similar to that used here and free of stray radiation would substantially reduce these problems and would be of great utility for x-ray astronomy.

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REFERENCES


