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DETECTION OF H I 21 CENTIMETER ABSORPTION BY THE WARM NEUTRAL MEDIUM

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ABSTRACT

We have detected H I 21 cm line absorption by the warm neutral medium (WNM) using the Westerbork synthesis radio telescope. The absorption was detected toward Cygnus A at LSR velocities of −40 and −70 km s^{-1}. These two velocity ranges were previously identified as being relatively free of cold absorbing clouds. The measured optical depth for the WNM along the line of sight to Cygnus A is $(8.9 \pm 1.9) \times 10^{-4}$ at −70 km s^{-1} and $(8.5 \pm 2.0) \times 10^{-4}$ at −40 km s^{-1}, with corresponding spin temperatures of 6000 ± 1700 and 4800 ± 1600 K, respectively. The volume filling factor for the WNM appears to be fairly high ($f \approx 0.4$).

Subject heading: Galaxy: fundamental parameters — ISM: atoms — ISM: structure — radio lines: ISM

1. INTRODUCTION

Early observations of the 21 cm line of neutral hydrogen in emission and absorption in the Galaxy showed that toward any given direction, the H I line seen in emission was always broader than the corresponding H I absorption line. In addition, most lines of sight showed a broad H I emission line with no corresponding H I absorption (Clark, Radhakrishnan, & Wilson 1962; Clark 1965; Radhakrishnan et al. 1972). These observations led to the proposal of a "raisin-pudding" model of the interstellar medium (Field, Goldsmith, & Habing 1969), in which dense cool H I clouds at 10^2 K (the cold neutral medium [CNM]) are enveloped by a warmer, lower density gas at 10^4 K (the warm neutral medium [WNM]). More recent models for the interstellar medium include a high filling factor, hot ionized medium at 10^6 K, which results from supernovae explosions (McKee & Ostriker 1977). The phases of the interstellar medium are thought to be in pressure equilibrium, although the relative filling factors of the different phases remain uncertain, and the filling factors may vary with position in galaxies (Brinks 1990; Braun & Walterbos 1992).

Kulkarni & Heiles (1988) point out that of all the phases of the interstellar medium (ISM), the WNM remains the least well understood. Although H I 21 cm emission from the WNM is detected easily in every direction in the sky, an accurate value for the temperature of the WNM is lacking. The standard method with which to determine the temperature of interstellar H I is to compare H I column densities that are determined by the observation of the 21 cm line in emission in a given region with those that are determined by the observation of 21 cm absorption toward background continuum sources (Clark 1965). The result is the excitation, or spin temperature, of the gas. The spin temperature, T_s, is thought to be close to the kinetic temperature in most Galactic environments. There are three well-known problems with this method. The first is that one has to interpolate H I column densities determined off-source to the position of the continuum source. For the WNM, this is not a severe problem, since the column density distribution appears to be fairly smooth on scales ≥10′ (Kalberla, Schwarz, & Goss 1985). Second, when looking for absorption by the WNM, there is the confusion caused by the plethora of absorption lines arising in the CNM. And third, there is the problem of having both emission and absorption in the on-source beam and the related problem of "stray radiation" or emission coming in through the sidelobes of the telescope beam. This is especially a problem for single-dish observations, for which beam sizes are typically much larger than the background continuum sources.

Kulkarni & Heiles (1988) review measurements of the temperature of the WNM. They conclude that the current data, which entail mostly lower limits to T_s, are consistent with a temperature range of 5000–8000 K for most of the WNM. They emphasize that the current data are sparse and that "observational confirmation of this conclusion is *crucial*." The single existing experiment that claims detection of absorption by the WNM is the one by Mebold & Hills (1975). They studied H I emission and absorption in the vicinity of the bright extragalactic radio source Cygnus A using the Effelsberg 100 m telescope. Their experiment consisted of eight off-source pointings that encircled the continuum source, in order to determine the H I column density distribution in the region, and on-source observations to look for absorption. They found two interarm velocity ranges with no narrow absorption features due to the CNM. At these velocities, their on-source spectrum of Cygnus A shows H I in *emission*; however, the amount of emission seen on-source is less than that expected from the interpolation of the off-source pointings to the source position. From this they *infer* absorption toward the continuum source. Mebold & Hills estimate an optical depth for the WNM between 6×10^{-4} and 11×10^{-4} and a spin temperature between 6400 and 7800 K. Kalberla, Mebold, & Reich (1980) reanalyzed the data, correcting for stray radiation, and reduced the spin temperature estimates by about 20%.

In this Letter, we present a direct verification of absorption toward Cygnus A in the CNM-free velocity ranges using the Westerbork synthesis radio telescope (WSRT). We then derive the spin temperature for the WNM in the two CNM-free velocity ranges using the WSRT absorption measurements and emission spectra from the Effelsberg and Dwingeloo telescopes. We discuss these results in terms of standard equilibrium models for the two-phase neutral atomic ISM.

2. OBSERVATIONS OF CNM-FREE REGIONS TOWARD CYGNUS A

The CNM-free LSR velocity ranges toward Cygnus A are from −40 to −36 km s^{-1} and from −63 to −78 km s^{-1}, corresponding to interarm velocities, between the Orion (0 km

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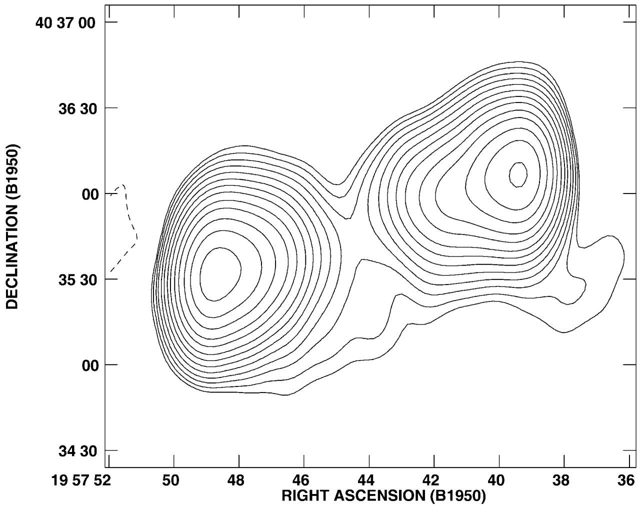

FIG. 1.—A continuum image of Cygnus A at 1.4 GHz that was made using line-free channels from the WSRT observations. The total flux density is 1575 Jy. The contours are a geometric progression in the square root of 2. The first level is 5 Jy $beam^{-1}$. The dotted contours are negative levels. The FWHM of the Gaussian-restoring beam is 30″ × 15″, with the major axis oriented north-south.

s^{-1}), Perseus (−50 km s^{-1}), and outer (−85 km s^{-1}) spiral arms (Mebold & Hills 1975). We have searched for absorption by the WNM at these interarm velocities using the WSRT. Using an interferometer mitigates the problems of confusion caused by stray radiation and in-beam emission. Observations were made on 1996 May 24 and 25, July 15 and 16 and 1997 June 28 and 29, August 22 and 23 for 12 hr each day. The total bandwidth was 1.25 MHz with 255 spectral channels after Hanning smoothing, corresponding to a 1 km s^{-1} velocity resolution, centered at an LSR velocity of −45 km s^{-1}. The absolute flux calibration and initial phase calibration were performed using 3C 286, and residual phase errors were corrected through self-calibration using a continuum data set made from line-free channels.

An accurate bandpass was determined using frequency switching to "high" and "low" frequencies by ±1.25 MHz on Cygnus A itself. The cycle time for the bandpass calibration was 2 hr, with a 50% duty cycle, and the bandpass for each cycle was the average of the high- and low-frequency settings. An estimate of the accuracy of the bandpass calibration process was obtained by applying the high-frequency bandpass solutions to the low-frequency spectra. The residual fractional deviations were generally $\leq 1.7 \times 10^{-4}$. We adopt this value as a conservative estimate of the optical depth errors introduced by the bandpass calibration process.

The visibility data from each day's observation were reduced independently using the Astronomical Image Processing System (AIPS). The continuum emission was subtracted using the AIPS task UVLIN, which performs a linear fit to the line-free channels for each visibility, and the data from the 8 days were then combined. Spectral line image "cubes" were constructed from the combined data, and the point response function of the array deconvolved, using the AIPS task IMAGR. The Gaussian-restoring CLEAN beam had an FWHM = 30″ × 15″ with a major axis oriented north-south.

The continuum image of Cygnus A made from the line-free channels is shown in Figure 1. The observed total flux density at 1.4 GHz for Cygnus A was within 2% of the expected value

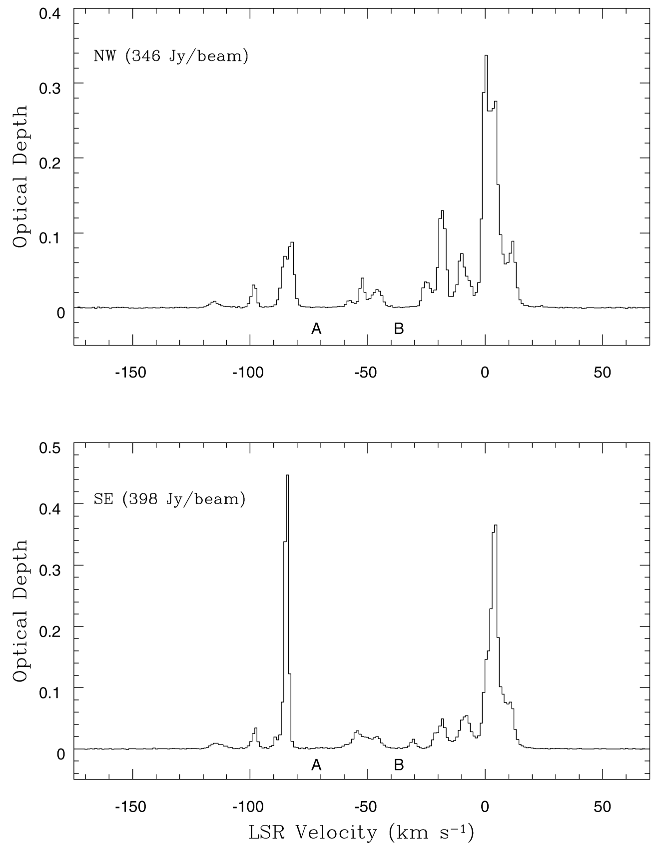

FIG. 2.—The upper frame shows the H I absorption spectrum toward the northwest peak of Cygnus A. The spectral resolution in this, and subsequent, spectra is 1 km s^{-1} $channel^{-1}$. The spectrum has been converted to the optical depth using the continuum surface brightness of 346 Jy $beam^{-1}$ at the resolution of Fig. 1. The velocity scale is the LSR. The CNM-free velocity ranges are labeled "A" and "B." The lower frame shows the corresponding spectrum of the southeast peak, where the continuum surface brightness is 398 Jy $beam^{-1}$.

of 1575 Jy (Baars et al. 1977). The source is characterized by two "hot spots" of emission at the source extremities, separated by 2′, with a low-frequency "bridge" of emission connecting the two hot spots. In the following section, we analyze spectra taken at the northwest (NW) and southeast (SE) hot spots. The peak surface brightness is 346 Jy $beam^{-1}$ for the NW hot spot and 398 Jy $beam^{-1}$ for the SE hot spot.

The H I absorption spectra toward the SE and NW peaks of Cygnus A are shown in Figure 2. The spectra show deep, narrow lines due to the CNM, clustered around the spiral arm velocities (0, −50, and −85 km s^{-1}), with optical depths approaching 0.5. There are significant variations in the optical depth for these narrow lines between the two lines of sight separated by 2′. Small-scale structure in the CNM is a well-studied phenomenon (Dieter, Welch, & Romney 1976; Diamond et al. 1989; Deshpande et al. 1992; Frail et al. 1994; Davis, Diamond, & Goss 1996), and a detailed analysis of the CNM structure toward Cygnus A will be presented elsewhere. The rms noise per channel in these spectra is 0.1 mJy $channel^{-1}$, corresponding to an rms optical depth (σ) of about 2.5×10^{-4} $channel^{-1}$.

Note the lack of deep, narrow absorption features in the interarm velocity ranges from −40 to −36 km s^{-1} (region B in the spectra) and from −63 to −78 km s^{-1} (region A), as first pointed out by Mebold & Hills (1975). Figures 3 and 4 show these same spectra with an expanded flux and optical

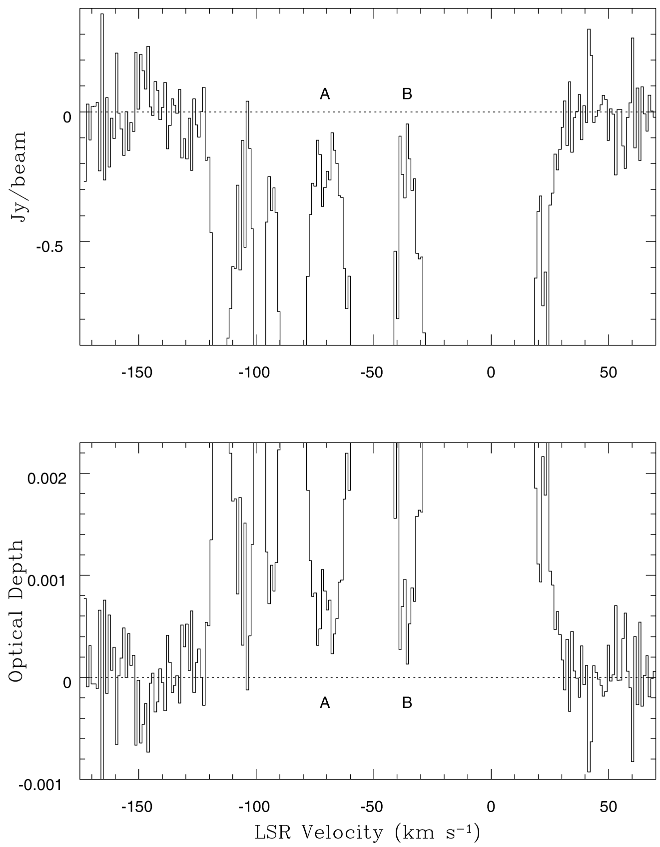

FIG. 3.—The upper frame shows the H I absorption spectrum toward the northwest peak of Cygnus A, after subtracting the continuum surface brightness of 346 Jy beam^{-1}. The velocity scale is the LSR. The lower frame shows the same spectrum converted to the optical depth using the continuum surface brightness of 346 Jy beam^{-1}. The optical depth scale has been expanded to show the low optical depth absorption. The CNM-free velocity ranges A and B are indicated.

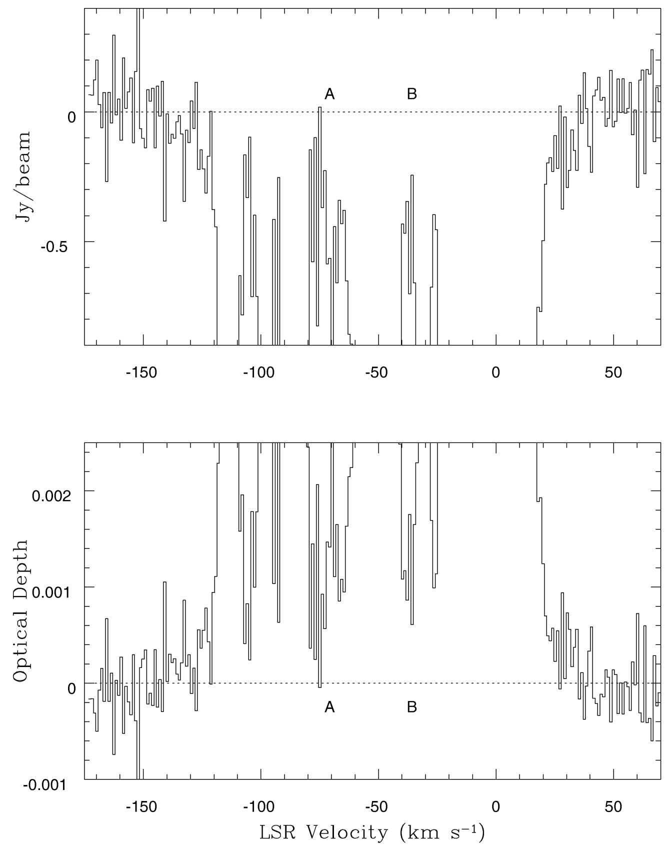

FIG. 4.—The upper frame shows the H I absorption spectrum toward the southeast peak of Cygnus A, after subtracting the continuum surface brightness of 398 Jy beam^{-1}. The velocity scale is the LSR. The lower frame shows the same spectrum converted to the optical depth using the continuum surface brightness of 398 Jy beam^{-1}. The optical depth scale has been expanded to show the low optical depth absorption. The CNM-free velocity ranges A and B are indicated.

depth scale in order to investigate possible absorption in these two CNM-free velocity ranges. The observed (continuum-subtracted) surface brightnesses in regions A and B appear to be significantly below zero in all the spectra. The mean optical depth values in regions A and B are listed in Table 1. The errors are a (quadratic) sum of the sensitivity error (i.e., the rms in off-line channels after averaging over the specified number of channels) and the estimated error due to bandpass calibration.

The optical depth in velocity region B is marginally higher toward the SE source relative to the NW source (1.8 σ). However, the SE source spectrum shows a narrow absorption line by the CNM at -30 km s^{-1}, which is not seen toward the NW source. The wing of this line might perturb the measured value in region B. Similarly, the spectrum of the SE component in velocity region A shows what might be a narrow, weak absorption component at -69 km s^{-1}. In the analysis below, we use the optical depths in regions A and B averaged over both SE and NW spectra (the third row in Table 1), with errors as dictated by each measurement.

We are confident that the finite optical depths observed at the CNM-free velocities are reliable for a number of reasons. First, the observed optical depths are significantly higher than the estimated accuracy of the bandpass calibration. Second, we have analyzed spectra from data taken from the four epochs separately (1996 May and July and 1997 June and August) and obtain consistent results for each epoch. And third, we have fitted Gaussian models to the strong absorption lines nearest

TABLE 1
PARAMETERS FOR THE WNM TOWARD CYGNUS A

Parameter	A (-67 to -76 km s^{-1})	B (-36 to -40 km s^{-1})
Optical depth: NW ($\times 10^{-4}$)	6.8 ± 1.9	6.0 ± 2.0
Optical depth: SE ($\times 10^{-4}$)	11 ± 1.9	11 ± 2.0
Mean optical depth ($\times 10^{-4}$)	8.9 ± 1.9	8.5 ± 2.0
T_B (Effelsberg) (K)	5.6 ± 1	4.0 ± 1
T_B (Dwingeloo) (K)	4.7 ± 2	4.5 ± 2
Mean T_B (K)	5.3 ± 1	4.1 ± 1
T_s (K)	6000 ± 1700	4800 ± 1600

in velocity to the CNM-free regions, and we find that the finite optical depths seen in these regions are not due to the wings of the strong lines. We should emphasize that we cannot rule out a model in which the finite optical depths seen at the CNM-free velocities toward Cygnus A are due to a "continuum" of low optical depth cold clouds. If this were the case, the optical depths quoted in Table 1 would be strictly upper limits to the true optical depth of the WNM, and the spin temperature values quoted below then become lower limits.

3. DISCUSSION

We can combine our measurement of the H I 21 cm optical depth of the WNM with the emission measurements of Mebold & Hills (1975) to obtain a lower limit to the spin temperature of the WNM, using the low optical depth approximation: $T_B = \tau T_s$, where τ is the optical depth to 21 cm absorption and T_B is the brightness temperature of the 21 cm emission in the absence of absorption.

One measurement of the emission spectrum in the direction of Cygnus A is the Effelsberg 100 m spectrum of Mebold & Hills (1975), which entailed the average of eight emission profiles taken at distances of 20′ from Cygnus A in a symmetric star pattern centered on Cygnus A. The brightness temperatures in velocity ranges A and B are given in the fourth row of Table 1. These are the values of Mebold & Hills reduced by 20% to correct for stray radiation (Kalberla et al. 1980). Mebold & Hills quote an error of 1 K for these measurements. A second measurement is from the all-sky H I survey of Hartmann & Burton (1997), using the Dwingeloo 25 m telescope and corrected for stray radiation. The Dwingeloo values are given in the fifth row of Table 1, where we have averaged four measurements surrounding Cygnus A at distances of about 20′. The errors represent the scatter in the measurements. Although the resolutions of the two observations are different (11′ for Effelsberg and 30′ for Dwingeloo), the T_B values agree to within the errors. For the calculation of spin temperatures, we use the (error-weighted) mean T_B values listed in the sixth row of Table 1. The resulting spin temperature values for velocity regions A and B are listed in the seventh row of Table 1, where the errors are a quadrature sum of errors on the brightness temperature measurement and the optical depth measurement.

The Galactic coordinates for Cygnus A are $l = 76°$, $b = 5.°8$. The implied distances to the gas in velocity ranges A and B are about 12 and 9 kpc, respectively, as derived from the Galactic rotation curve of Burton (1988). The height of this gas from the plane, z, is then $z \approx 1$ kpc. A very rough estimate of the path length through the gas can be derived by assuming that the velocity ranges are set by Galactic rotation, leading to 0.9 and 0.4 kpc for A and B, respectively. Then using the H I column densities calculated from Table 1 leads to a mean density for the WNM in velocity ranges A and B toward Cygnus A of $\langle n_{\rm wnm} \rangle \approx 0.03$ cm^{-3}. The ISM pressure at $z = 1$ kpc is thought to be about 5×10^{-14} dyn cm^{-2} (Kulkarni & Heiles 1988, eq. [3.30]). This pressure, coupled with the mean temperature of 5400 K for the WNM from Table 1, leads to a density of $n_{\rm wnm} = 0.07$ cm^{-3}. Hence, the volume filling factor, f, for the WNM at $z = 1$ kpc is $f \equiv (\langle n_{\rm wnm} \rangle / n_{\rm wnm}) \approx 0.4$. This value of f is consistent with the estimate of Kulkarni & Heiles (1988) of $f = 0.6$ for the sum of the warm neutral and warm ionized medium, with the dominant component being the WNM in the case where magnetic fields and cosmic-ray pressures are substantial. While the uncertainties in the above calculation are significant (in particular, the use of small-velocity gradients to derive path lengths), the general implication is that the volume filling factor for the WNM appears to be fairly high.

The H I spin temperature is thought to be driven to the kinetic temperature of the gas through the process of resonant scattering of ambient Lyα photons (Field 1958). This process depends critically on the local Lyα photon density, which in turn depends on the ionization rate due to cosmic rays and soft X-rays since the H I is opaque to external Lyα photons. Based on the analysis of Galactic low-density regions by Deguchi & Watson (1985), Kulkarni & Heiles (1988) state that "the ionization rate is large enough in the Galactic environment to make the spin temperature (T_s) $\approx$ kinetic temperature (T_k) for almost any H I cloud observable in the 21 cm line." The current limit to the diffuse Galactic Lyα photon density in the solar neighborhood is $n_{\rm Ly\alpha} < 2.5 \times 10^{-6}$ cm^{-3} (Holberg 1986). This limit is sufficient to maintain $T_s \approx T_k$ in the WNM if $T_k \sim 3000$ K (Field 1958). If the value of $n_{\rm Ly\alpha}$ is considerably below 10^{-6} cm^{-3} in the WNM, then T_s could fall significantly below T_k. For example, Corbelli & Salpeter (1993) find that the temperature equilibrium between T_s and T_k may not hold in the outer disks of spiral galaxies, where N(H I) is less than or equal to a few times 10^{19}, if the only source of ionizing radiation is the extragalactic background. Until a direct measurement of $n_{\rm Ly\alpha}$ in the WNM becomes available, we can only assume that $T_s \approx T_k$ in the disk of the Galaxy.

The most detailed analysis of the equilibrium state of neutral hydrogen in the interstellar medium is the work of Wolfire et al. (1995). The primary heating mechanism is photoelectric emission from dust grains, while cooling is dominated by fine-structure lines from heavy elements (predominantly carbon) and by hydrogen recombination lines in warmer regions. In their standard model for neutral hydrogen in the Galactic plane, they show that two stable phases exist: (i) the CNM with T_k between 40 and 200 K, and (ii) the WNM with T_k between 5500 and 8700 K, for ISM pressures in the range of $(1\text{–}5) \times 10^{-13}$ dyn cm^{-2}. It is interesting that the measured values of T_s in the lower pressure (i.e., larger z) WNM toward Cygnus A (Table 1) are generally consistent with these ranges for the neutral, two-phase ISM model of Wolfire et al. (1995). Corbelli & Salpeter (1993) point out that equality between T_s and T_k could be used to argue that the ionizing radiation field for the WNM is well above the extragalactic background and, hence, that "relevant energy inputs from local sources become necessary." While the current data toward Cygnus A are consistent with the value of T_s being close to the model value of T_k for the WNM, more accurate values for T_s and T_B for the neutral hydrogen, and $n_{\rm Ly\alpha}$, are needed to provide a fully constrained physical model for the Galactic WNM.

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