

DETECTION OF [N II] λ 5755 EMISSION FROM LOW-DENSITY IONIZED INTERSTELLAR GAS

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ABSTRACT

The extremely faint, temperature-sensitive “auroral” emission line [N II] λ 5755 has been detected from the low-density ionized gas along the sight line toward $l = 130^\circ 0$, $b = -7^\circ 5$ using the Wisconsin H α Mapper. The intensity of this emission line, relative to the red nebular line [N II] λ 6584, is found to be twice that observed in bright, classical H II regions surrounding O stars. This implies that the electron temperature of the ionized gas along this sight line is about 2000 K higher than the H II regions and that the enhanced [N II] λ 6584/H α and [S II] λ 6716/H α intensity ratios in this low-density gas are due at least in part to an elevated temperature.

Subject headings: H II regions — ISM: general

1. INTRODUCTION

Regions of nearly fully ionized hydrogen, having a temperature near 10^4 K and an electron density of order 10^{-1} cm $^{-3}$, are widespread throughout the disk and halo of the Milky Way and other galaxies. The source of the ionization and heating of this diffuse ionized gas is not yet understood. However, important clues can be found in its optical spectrum, which is characterized by high [N II] λ 6584/H α and [S II] λ 6716/H α line intensity ratios relative to the ratios observed in the much brighter, higher density H II regions around O stars (e.g., Rand 1997; Haffner, Reynolds, & Tuft 1999). Such elevated ratios indicate ionization/excitation conditions in the diffuse ionized gas that differ significantly from conditions in the classical H II regions.

Although photoionization models incorporating a very dilute ionizing radiation field (a low ionization parameter) are generally successful in producing the elevated line ratios (e.g., Sokolowski 1991; Domgörgen & Mathis 1994; Greenawalt, Walterbos, & Braun 1997), they fail to explain some important details of the observations. In particular, pure photoionization models cannot account for the very high [N II]/H α , [S II]/H α , and [O II]/H α ratios (near unity and above) observed far from the midplane, nor can they explain the observed constancy of [S II]/[N II], even when the variations in [S II]/H α and [N II]/H α from direction to direction are large (e.g., see Rand 1997, 1998; Ferguson, Wyse, & Gallagher 1996; Tüllmann et al. 2001; Mathis 2000). Haffner et al. (1999) and Reynolds, Haffner, & Tuft (1999, 2000) have shown that these observations could be explained if the variations in [S II]/H α and [N II]/H α were the result of variations in the electron temperature of the emitting gas rather than variations in the ionization parameter. Such temperature variations require the existence of an additional source of heat in the low-density gas that dominates over the photoionization heating (Reynolds et al. 1999).

One prediction of this idea is that the electron temperature in regions of faint, low-density ionized gas, where the [N II]/H α ratios are high, must be significantly greater than the temperature in the higher density, bright H II regions, where the [N II]/H α ratio is relatively low. A standard method of determining electron temperatures in ionized interstellar gas is to measure the [N II] λ 5755/[N II] λ 6584 line intensity ratio.

Since [N II] λ 6584 is one of the brightest lines emitted by diffuse ionized gas, comparable in intensity to the H α (Haffner et al. 1999), these nitrogen lines are a potentially useful diagnostic, provided that a sufficiently sensitive spectrometer is available to detect the much weaker 5755 Å transition. For densities below 10^4 cm $^{-3}$, the situation for the ionized regions considered here, Osterbrock (1989) gives the volume emissivity ratio for the nitrogen lines simply as

$$\frac{\epsilon(5755)}{\epsilon(6584)} = 0.192e^{-25,000/T_e} \quad (1)$$

Below we present spectra of H α , [N II] λ 6584, and [N II] λ 5755 obtained with the Wisconsin H α Mapper (WHAM) in a direction that samples faint low-density gas and in directions toward bright, higher density H II regions. The results provide evidence for a significant temperature difference between the two types of ionized regions.

2. OBSERVATIONS AND RESULTS

The observations were made with the WHAM spectrometer, located on Kitt Peak and operated remotely from Madison, Wisconsin (Haffner et al. 1999; Tuft 1997). In 1998 October and 1999 November, long-integration spectra were obtained of a 3.8 Å (200 km s $^{-1}$)–wide spectral interval centered near the LSR velocity of the [N II] λ 5755 line. The spectral resolution was 12 km s $^{-1}$, and the beam on the sky was 1 $^\circ$ 0 in diameter. The observations consisted of a series of integrations (each 300 or 600 s) toward $l = 130^\circ 0$, $b = -7^\circ 5$, which samples diffuse low-density gas. Between each of these “on-source” observations, an integration of approximately equal length was made toward one of a number of higher Galactic latitude, even fainter “off-source” directions: $135^\circ 0$, $-30^\circ 0$; $135^\circ 0$, $-35^\circ 0$; $135^\circ 0$, $-40^\circ 0$; $142^\circ 5$, $-22^\circ 5$; and $157^\circ 0$, $-24^\circ 5$. This technique is described by Tuft, Reynolds, & Haffner (1998) and has been used to detect very faint optical emission lines from high-velocity H I clouds. Observations of the fainter, off-source directions are necessary because the spectra are contaminated by very weak, unidentified atmospheric emission lines that are comparable to or brighter than the interstellar emission (N. R. Hausen, R. J. Reynolds, L. M. Haffner, & S. L. Tuft 2001, in preparation; Tuft et al. 1998). By subtracting the average of the off-source spectra from the on-source spectrum, we obtain a pure interstellar spectrum of [N II] λ 5755 toward $l = 130^\circ 0$, $b = -7^\circ 5$. Because diffuse ionized gas covers the entire

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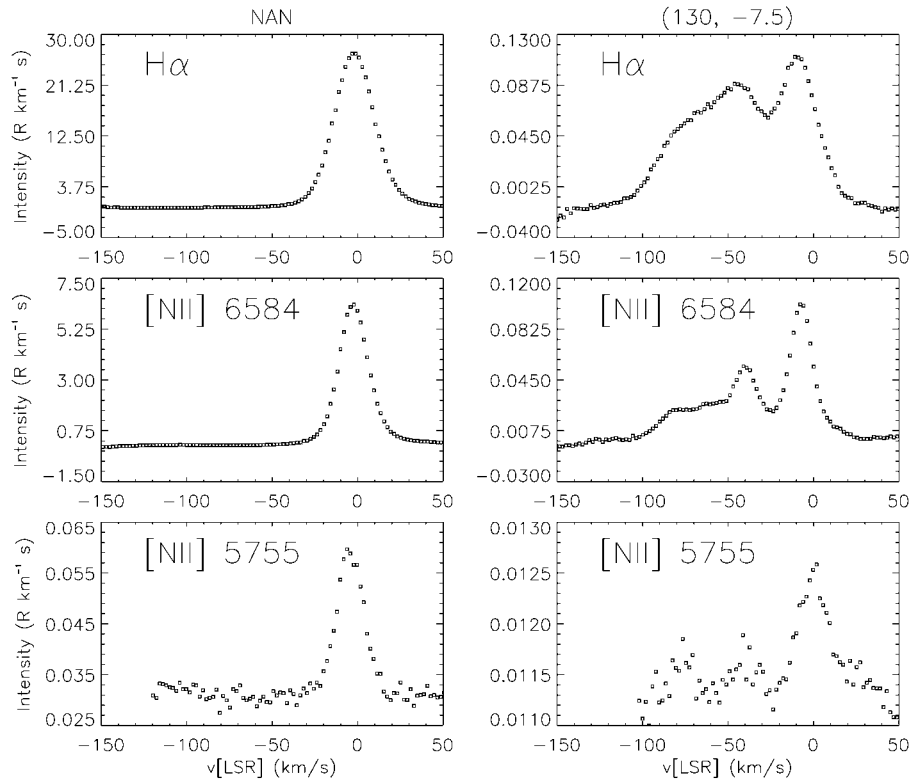


FIG. 1.—Resulting WHAM spectra of $H\alpha$, [N II] $\lambda 6584$, and [N II] $\lambda 5755$ toward $l = 130^\circ$, $b = -7.5^\circ$ and toward the O star H II region S117 (North America Nebula). The vertical scatter in the data points provides a measure of the observational uncertainty. Except for the $\lambda 5755$ spectra, the uncertainties are comparable to or less than the size of the symbol.

sky, this process also subtracts a small amount of the interstellar emission. For example, the average $H\alpha$ and [N II] $\lambda 6584$ intensity in the off-source directions is 16% and 20%, respectively, that toward 130° , -7.5° . For consistency, the same procedure was used to obtain spectra of $H\alpha$ and [N II] $\lambda 6584$ for this direction as well as $H\alpha$, [N II] $\lambda 6584$, and [N II] $\lambda 5755$ for seven bright H II regions around O stars (this “on” minus “off” technique was not really necessary in these cases because the interstellar emission was always much brighter than the atmospheric emission—except the geocoronal $H\alpha$ line, which is removed by a different procedure; see Reynolds et al. 1998).

The direction 130° , -7.5° is within the region mapped in $H\alpha$, [N II] $\lambda 6584$, and [S II] $\lambda 6716$ by Haffner et al. (1999). This particular sight line was selected because the $H\alpha$ emission is relatively bright, making it possible to detect the exceedingly faint [N II] $\lambda 5755$ line, and because the [N II] $\lambda 6584/H\alpha$ and [S II] $\lambda 6716/H\alpha$ ratios (0.43 and 0.27, respectively) are characteristic of diffuse low-density gas and are significantly higher than the ratios in the bright H II regions (e.g., for the H II regions considered here, the average ratios are 0.27 and 0.08, respectively). Radial velocity components ranging from near the LSR out to about -80 km s^{-1} are clearly present in the $H\alpha$ and [N II] $\lambda 6584$ profiles, indicating that the ionized gas is spread along a large portion of the sight line. A very extended, faint H II region associated with the B1 star ϕ Per (4° away and 220 pc distant) appears to dominate the profile near 0 km s^{-1} , while the emission at the most negative velocities is associated with gas more than 2 kpc distant and 300 pc from the midplane in the Perseus arm or beyond (see Haffner et al. 1999).

The resulting “on” minus “off” spectra are shown in Fig-

ure 1 for 130° , -7.5° and for one of the H II regions. The [N II] $\lambda 5755$ spectrum toward 130° , -7.5° has a total on-source integration time of 12,300 s (19,500 s off-source) and shows the first detection of this nitrogen line from low-density ionized gas. Integration times for $H\alpha$ and [N II] $\lambda 6584$ in this direction were 660 and 1020 s (720 and 1200 s off-source), respectively, while for the H II regions the integration times ranged 30–60 s for the $H\alpha$, 60–120 s for [N II] $\lambda 6584$, and 120–1200 s for [N II] $\lambda 5755$.

Line intensities were calculated by fitting Gaussian emission components to the spectra. For 130° , -7.5° the [N II] $\lambda 6584$ profile indicates four radial velocity components at -81 , -61 , -40 , and -7 km s^{-1} . In the $H\alpha$ spectrum, these components are not as well defined because of the larger thermal broadening of the hydrogen. Gaussians at these four velocities were fitted to each of the three spectra toward 130° , -7.5° , while single Gaussians were used for the H II region spectra. This produced good fits in all cases, and the results are listed in Table 1. The intensity calibrations of the nitrogen lines are based on the $H\alpha$ calibration with small corrections for instrument response and atmospheric transmission. Since the principal goal is to compare emission-line ratios between the 130° , -7.5° direction and the bright H II regions, small systematic errors in the absolute calibrations of the individual lines will not affect our conclusions. For [N II] $\lambda 5755$, the position of the baseline was the principal source of uncertainty for the component intensities, and the listed uncertainties were derived by examining many fits using various adopted baselines.

Because interstellar extinction has only a small effect on the emission-line ratios, no extinction corrections have been made. The exciting stars for the bright H II regions in our sample have

TABLE 1
RESULTS

Region Name ^a	H α (R) ^b	[N II] λ 6584/H α (Energy) ^c	$100 \times ([\text{N II}] \lambda 5755/[\text{N II}] \lambda 6584)$ (Energy) ^c
C1	1.51 ± 0.08	0.38 ± 0.06	1.3 ± 0.6
C2	2.14 ± 0.10	0.21 ± 0.03	0.3 ± 0.3
C3	2.06 ± 0.10	0.59 ± 0.04	0.4 ± 0.2
C4	4.15 ± 0.14	0.52 ± 0.04	1.33 ± 0.12
C (total)	10.11 ± 0.18	0.43 ± 0.01	0.96 ± 0.21
S117	800 ^d	0.202 ± 0.005	0.45 ± 0.03
S132	136 ± 2^e	0.218 ± 0.005	0.41 ± 0.03
S184	145 ± 2^e	0.294 ± 0.008	0.44 ± 0.03
S220	339 ± 5	0.383 ± 0.012	0.38 ± 0.02
S252	202 ± 4^e	0.270 ± 0.009	0.49 ± 0.03
S261	68 ± 1^e	0.353 ± 0.009	0.50 ± 0.06
S264	157 ± 2	0.216 ± 0.006	0.42 ± 0.04

^a C1, C2, C3, and C4 refer to components at radial velocities -81 , -61 , -40 , and -7 km s⁻¹, respectively, for the line of sight 130° , $-7^\circ 5'$; C (total) is the velocity-integrated line profile. The “S” designation for the H II regions refers to the Sharpless Catalog number (Sharpless 1959).

^b $1 \text{ R} = 10^9/4\pi$ photons cm⁻² s⁻¹ sr⁻¹, or 2.41×10^{-7} ergs cm⁻² s⁻¹ sr⁻¹ for H α .

^c These are intensity ratios (not photon ratios).

^d The H α intensity of this region (NGC 7000) is used as the absolute intensity standard (Scherb 1981).

^e These regions do not fill WHAM’s 1° diameter beam (listed H α intensities are averaged within the beam).

values for E_{B-V} that range from 0.12 to 0.71 (see Reynolds 1988), which according to Mathis (1983) would require correction factors of 1.03–1.10 to the observed [N II] λ 5755/[N II] λ 6584 intensity ratios. The H I column density toward $130^\circ 0'$, $-7^\circ 5'$ is 1.5×10^{20} cm⁻² (Hartmann & Burton 1997), implying an $E_{B-V} \approx 0.3$, similar to the average (0.4) toward the H II regions. Thus, the comparison of the ratios between this sight line and the H II regions should not be affected significantly by extinction. The principal effect of applying extinction corrections would be to increase all the temperatures derived from equation (1) by about 200 K.

The [N II] λ 5755/[N II] λ 6584 and [N II] λ 6584/H α line intensity ratios for the H II regions and for $130^\circ 0'$, $-7^\circ 5'$ are plotted in Figure 2. The results listed in Table 1 for the individual velocity components toward $130^\circ 0'$, $-7^\circ 5'$ suggest that there may be large variations in the ratios from component to component.

Components 1 and 4, for example, appear to have higher [N II] λ 5755/[N II] λ 6584 ratios than components 2 and 3. However, because of severe blending between the components, except for component 4, and because of the relatively low signal-to-noise ratio of the [N II] λ 5755 spectrum, only the results for component 4 and for the integrated line profile (the sum of all four velocity components) are plotted in Figure 2.

3. DISCUSSION AND CONCLUSIONS

The emission line [N II] λ 5755 has been detected for the first time in the faint “diffuse background,” making it possible to explore directly the electron temperature in the low-density ionized gas. Figure 2 clearly shows that toward $130^\circ 0'$, $-7^\circ 5'$ not only does the gas have a larger [N II] λ 6584/H α ratio than the bright H II regions (a long recognized characteristic of diffuse ionized gas) but the [N II] λ 5755/[N II] λ 6584 ratio is also larger, implying that the faint, diffuse gas has a significantly higher electron temperature T_e than the gas in the H II regions. For the H II regions, derived values of T_e from equation (1) range from 6400 to 6900 K, while toward $130^\circ 0'$, $-7^\circ 5'$, $T_e = 9400 \pm 400$ K (component 4) and 8400 ± 500 K (the integrated profile). Thus, at least for this sight line the enhanced [N II] λ 6584/H α is due in part to an elevated temperature.

To examine more quantitatively the relationship between the intensity ratios and electron temperature, we have plotted as a solid line in Figure 2 the ratios predicted for various temperatures based on equation (1) and the relationship between [N II] λ 6584/H α and temperature presented by Haffner et al. (1999). Interestingly, nearly all of the observations lie above this line. This suggests that no single temperature can account for the observed ratios, not even toward the bright H II regions. The relationship between T_e and [N II]/H α is based on the fact that in photoionized interstellar gas, $N^+/N \approx H^+/H$ (e.g., Sembach et al. 2000). Thus, the offset between the solid line and the observations could be explained if there were a large amount of N^{++} , specifically, if $N^{++} \approx N^+$. While this may be possible for some of the H II regions, it cannot be the explanation for the $130^\circ 0'$, $-7^\circ 5'$ observations, since the high [S II]/H α ratio implies a relatively low ionization state for the

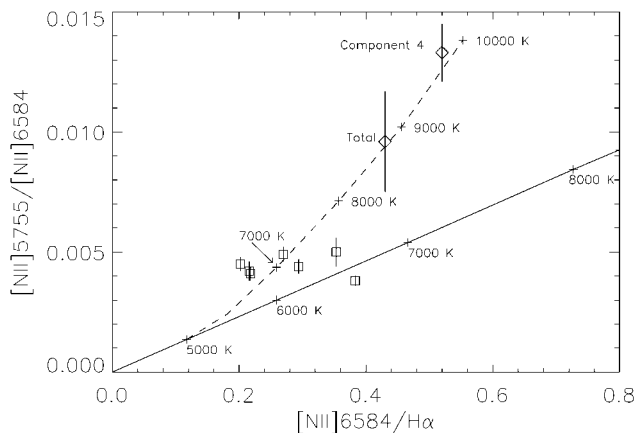


FIG. 2.—The λ 5755/ λ 6584 line intensity ratio plotted vs. λ 6584/H α for $130^\circ 0'$, $-7^\circ 5'$ (diamonds) and for the seven bright H II regions (squares). The solid line denotes the expected ratio based on Osterbrock (1989) and Haffner et al. (1999) for an emission region of uniform electron temperature. The dashed curve is the expected relationship if the emission is from an equal mixture (by emission measure) of gas at 5000 K and gas at a higher temperature indicated along the curve (see text).

gas (Haffner et al. 1999). A large (factor of 2) error in the adopted value for the gas-phase abundance N/H also seems improbable (see Meyer, Cardelli, & Sofia 1997; Afflerback, Churchwell, & Werner 1997). A more likely explanation is that a range of temperatures is present along the line of sight. In this case, [N II] $\lambda 5755$, with a higher excitation energy (4.04 eV) than that (1.89 eV) of [N II] $\lambda 6584$, is produced preferentially in the higher temperature regions, resulting in a temperature derived from [N II] $\lambda 5755$ /[N II] $\lambda 6584$ that is higher than the temperature derived from [N II] $\lambda 6584$ /H α . The dashed curve in Figure 2 represents a very simple case in which there is an equal mixture (by emission measure) of gas at two temperatures, half at 5000 K and half at the higher temperature indicated along the curve. While this fit is certainly not unique, and such bimodal temperatures are probably not realistic, it demonstrates that a mixture of temperatures can readily explain the observed ratios and that toward 130°0, -7°5 at least some of the gas has a significantly higher temperature than in the denser H II regions.

The direction 130°0, -7°5 was chosen in part because of its relatively high H α intensity. If an inverse relationship exists between temperature and density, then sight lines with fainter emission (lower densities) may have an even higher temperature than that derived for 130°0, -7°5. Furthermore, the derived temperature for 130°0, -7°5 itself would be an underestimate in this case, since higher temperature “offs” would

result in a slight oversubtraction of [N II] $\lambda 5755$ relative to [N II] $\lambda 6584$.

The detection of the [N II] $\lambda 5755$ emission has therefore provided strong evidence for a temperature difference between diffuse, low-density ionized gas and denser, classical H II regions. However, to explore more fully temperatures and possible variations in temperature within the diffuse ionized medium itself, many additional observations will be needed, observations in directions farther from the midplane, where the [N II] $\lambda 6584$ /H α and [S II] $\lambda 6717$ /H α ratios are even larger (and temperatures are higher?) and where the influence of individual O and B stars is less. Unfortunately, because [N II] $\lambda 5755$ is so weak, the use of this line for extensive studies of such faint regions is problematic; in fact, all single-ion diagnostics, which are insensitive to abundance and ionization state, appear to involve lines that are extremely faint. Less ideal, but brighter, temperature-sensitive line ratios, such as [O II] $\lambda 3727$ /H α , need to be investigated (Ferguson et al. 1996; Otte et al. 2001). Since [O II] has an excitation energy of 3.3 eV and an intensity comparable to that of H α , [O II]/H α perhaps could be used as a temperature diagnostic for diffuse ionized gas, particularly in combination with observations of [O I] $\lambda 6300$ and [O III] $\lambda 5007$ to monitor oxygen’s ionization state.

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