THE LISM AT OPTICAL WAVELENGTHS: SPECTRAL LINE STUDIES

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OPTICAL EMISSION LINE STUDIES

AND

THE WARM, IONIZED COMPONENT OF THE LOCAL INTERSTELLAR MEDIUM

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Abstract

Observations of diffuse, galactic Hα, [NII]λ6583, and [SII]λ6716 emission lines provide evidence for a warm ($\sim 10^4$ K), primarily ionized component of the interstellar medium distributed throughout the galactic disk. This component of the interstellar gas has an electron density $\approx$ 0.1-0.2 cm^{-3} and occupies about 10-30% of the interstellar volume. Interstellar Hα emission near the galactic poles, the dispersion measure of a nearby pulsar, and observations of interstellar gas flowing into the solar system indicate that this ionized component is an important constituent of the interstellar medium in the solar neighborhood. The intensity of the Hα background at high galactic latitudes implies that this component is maintained by an average hydrogen ionization rate in the vicinity of the Sun of (2-4) x 10^6 s^{-1} per cm^2 of galactic disk. The emission measure is 1.3-2.3 cm^{-6} pc toward the galactic poles. The sources of this ionization have not yet been identified but may include escaping Lyman continuum radiation from planetary nebulae, hot white dwarfs, and early type stars. Investigations of the regions surrounding ζ Oph (O9V), the nearest (d $\simeq$ 140 pc) O star, and α Vir (B1 IV), one of the nearest (d $\simeq$ 87 pc) early B stars, have revealed areas of enhanced Hα emission extending 6°-12° from each star. However, it appears that these stars do not contribute significantly to the more diffuse ionization within the local interstellar medium.

I. INTRODUCTION

Diverse observations of the interstellar medium have provided evidence for significant ionization of the interstellar gas outside bright, localized HII regions. These observations include pulsar dispersion measures (e.g., Taylor and Manchester 1977), free-free absorption of low frequency galactic radio emission (Ellis 1982), ultraviolet absorption lines (e.g., York 1983), and faint, optical interstellar emission lines (Reynolds, 1980). The development of the large aperture Fabry-Perot spectrometer (Roesler et al. 1978) has made it possible to

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detect and study very faint Hα, [NII], and [SII] emission from the diffuse interstellar medium. These emission lines have provided strong evidence for widespread regions of warm ($\simeq 10^4$ K), nearly fully ionized hydrogen distributed throughout the galactic disk.

Observations near the galactic equator (e.g., Reynolds 1983) reveal emission in every direction with a typical intensity (between the relatively bright, discrete emission regions) of about 1.3×10^{-6} ergs cm^{-2} s^{-1} sr^{-1}, while observations at higher latitudes (Reynolds 1984a) suggest that galactic Hα emission extends over the entire sky with an intensity that falls to $1.2\text{-}2.4 \times 10^{-7}$ ergs cm^{-2} s^{-1} sr^{-1} near the galactic poles. Although interstellar grains may scatter Hα photons from bright HII regions located near the galactic plane (Jura 1979), Hα observations toward high latitude reflection nebulae indicate that the intensity of this scattered component is small compared to the total background Hα intensity that is observed (Reynolds, Scherb, and Roesler 1973). Additional strong evidence that such scattered light is not a dominant source of background emission has been provided by the recent discovery that the [SII]λ6716/Hα intensity ratios in the diffuse background are approximately three to four times higher than the ratios found in the classical bright HII regions (Reynolds and Shih 1983).

The detection of the collisionally excited [NII]λ6583 and [SII]λ6716 emission in the galactic background places a lower limit of about 3000 K on the temperature of the emitting gas. If the H^+, N^+, and S^+ ions are well mixed within the ionized regions, then the observed widths of the emission lines indicate a temperature $\sim 10^4$ K (Reynolds, Roesler, Scherb 1977; Reynolds 1984b, in preparation). The absence of detectable [OI]λ6300 and [NI]λ5200 (Reynolds 1981; Reynolds, Roesler, and Scherb 1977) suggests a high fractional ionization of hydrogen (i.e., $H^+/H \gtrsim 0.75$). A typical electron density of 0.1-0.2 cm^{-3} within an ionized region has been derived from a comparison of emission measures and pulsar dispersion measures (Reynolds 1977). This analysis also indicates that the ionized component occupies about 10-30% of the interstellar volume.

II. THE Hα BACKGROUND AT HIGH GALACTIC LATITUDES

a) The Hα Intensity Distribution and The Emission Measure of the Galactic Disk Near the Sun

The Hα background near the galactic equator appears to originate from gas within the galactic disk that is distributed out to 3 kpc or more from the Sun (Reynolds 1983). On the other hand, observations at high galactic latitudes sample interstellar material that is more local to the Sun. A study of galactic Hα intensities at high latitudes has recently been carried out (Reynolds 1984a), and a summary of the results as they relate to the local Solar neighborhood are discussed below (Sections IIa, b).

Scans of the Hα were obtained toward 72 high galactic latitude pulsars as part of a program to compare emission measures and dispersion measures along lines of sight through the interstellar medium (in preparation). These observations include all of the pulsar directions listed by Manchester and Taylor (1981) that have galactic latitudes $|b| > 5°$ and declinations between -10° and +74°. (The siderostat which feeds the spectrometer cannot access declinations greater than +74°). Two additional scans that are not toward known pulsars were obtained near the north galactic pole. Figure 1 shows the distribution of observation directions in galactic coordinates. The galactic Hα intensity I_α for each of the 74 directions is plotted versus galactic latitude in Figure 2. The intensities are in rayleighs (R), where 1 R = 2.4×10^{-7} ergs cm^{-2} s^{-1} sr^{-1} at Hα. The open symbols in Figure 2 denote directions toward or within 5° of emission nebulosity that is visible on the Palomar Sky Survey red prints or on the photographic surveys of Sivan (1976) and Parker, Gull, and Kirshner (1979), and thus indicate directions that may not be sampling truly "background" Hα. The very large scatter in intensity within this subset of the data is evidence for significant contamination by discrete HII regions along some of the lines of sight. All except two of these potentially contaminated directions have galactic latitudes < 15°. The remaining "background" directions have Hα intensities that range from about 4-8 R for $|b| < 10°$ to about 1 R or a little less at $|b| > 50°$.

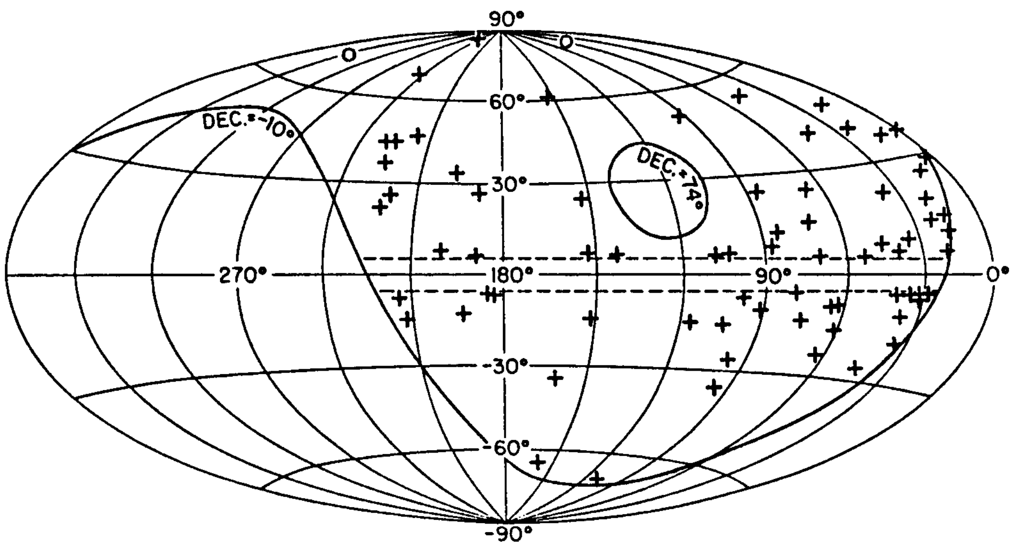

Fig. 1 - Directions of the high galactic latitude Hα scans. The map is in galactic coordinates centered on ℓ = 180°, b = 0°. The crosses represent directions toward pulsars and the two open circles represent additional very high latitude Hα observations which are not part of the pulsar survey.

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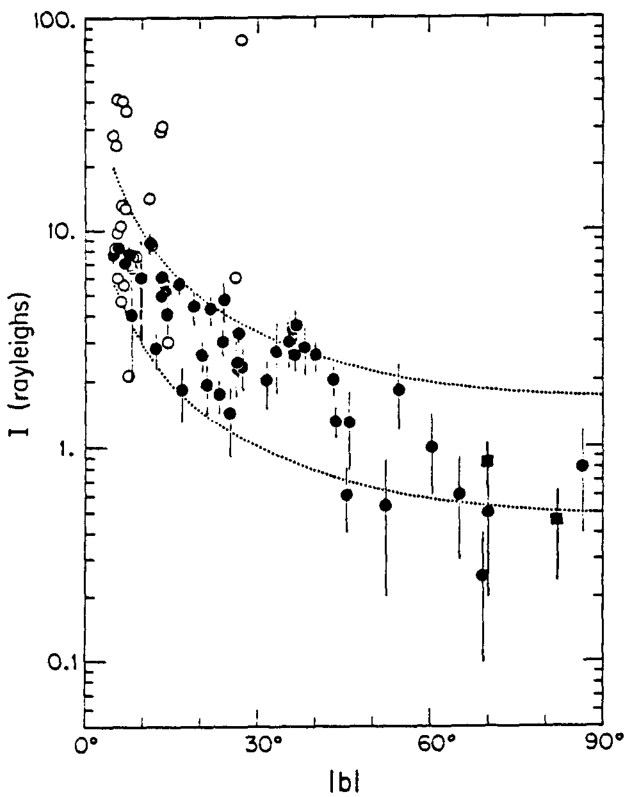

Fig. 2 - The Hα intensity in rayleighs (R) plotted versus the galactic latitude of the observation direction. The open circles represent directions toward or within 5° of emission nebulosity visible on photographic surveys. The squares represent the two additional very high latitude observations that are not part of the pulsar survey. The two dashed curves indicate the expected variation of intensity with galactic latitude for a uniformly emitting galactic disk with $I_\alpha \times \sin|b| =$ 0.5 R and 1.7 R and no extinction. 1 R = 2.42×10^{-7} erg cm^{-2} s^{-1} sr^{-1} at Hα or $10^6/4\pi$ photons cm^{-2} s^{-1} sr^{-1}.

The general decrease in Hα intensity with increasing latitude for $|b| > 10°$ is consistent with a disk-like distribution of the emitting gas, although the considerable scatter in intensities at any one value of $|b|$ suggests that the distribution is not entirely uniform. The two dashed curves in Figure 2 represent the expected variation of Hα intensity with galactic latitude for a uniformly emitting disk with values for $I_\alpha \times \sin|b|$ of 0.5 R and 1.7 R (and no extinction). These curves appear to bracket the data well. The clumping of data points near $I_\alpha \times \sin|b| \approx 1.7$ R for $30° < |b| < 40°$ and near $I_\alpha \times \sin|b| \approx 0.6$ R for $|b| > 60°$ could be merely statistical fluctuations in the small sample, or it may be an indication of large-scale features in the galactic Hα intensity distribution at high latitudes. Systematically lower values for $I_\alpha \times \sin|b|$ at $|b| > 60°$, for example, would occur if the Sun were located in a region of the interstellar medium with a lower than average Hα emissivity. More detailed information about the smaller scale distribution of diffuse emission at high latitudes will have to await a more intensive Hα mapping program.

The radius of the region surrounding the Sun within which the Hα emission at a given latitude originates depends upon the scale height of the emitting gas. Pulsar observations indicate a scale height of

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500-1000 pc for the density n_e of free electrons (Bridle and Venugopal 1969; Readhead and Duffett-Smith 1975). These electrons appear to be closely associated with the Hα emitting regions (Reynolds 1984a). If n_e decreases exponentially with increasing height z above the galactic plane, then the Hα emission from this gas would originate from a region with a scale height of H/2, since the Hα emissivity is proportional to n_e^2. This suggests that the emission at galactic latitude $|b| \gtrsim 60° - 70°$ is from gas located primarily within a cylinder of radius 150 pc centered on the Sun. Therefore, the mean value of $I_\alpha \times \sin|b|$ from all the data in Figure 2 appears to be $\approx$ 1 R with some evidence that the value decreases to $\approx$ 0.6 R within the more local 150 pc radius region surrounding the Sun. These values correspond to emission measures EM along a line of sight perpendicular to the galactic disk of 4.5 cm^{-6} pc and 2.7 cm^{-6} pc, respectively. A comparison of the emission measure with the estimated column density of electrons $N_e \simeq 1.5 \times 10^{20}$ cm^{-2} through the galactic disk in the Solar neighborhood (e.g., Harding and Harding 1982) indicates a mean electron density $n_e \simeq 0.11-0.18$ cm^{-3} within the ionized regions near the galactic plane.

b) The Hydrogen Recombination Rate and Possible Sources of Ionizing Radiation in the Local Interstellar Medium

The Hα intensity near the galactic poles provides a direct estimate of the hydrogen recombination rate r_g per cm^2 of galactic disk in the vicinity of the Sun. Specifically,

$$r_g = \frac{8\pi I_\alpha}{\varepsilon},$$

where I_α is the galactic Hα intensity (in photons cm^{-2} s^{-1} sr^{-1}), and ε is the average number of Hα photons produced per hydrogen recombination. The value of ε changes slowly with electron temperature and ranges from about 0.57 to 0.37 for temperature between 1250 K and 80,000 K, respectively (case B, Pengelly 1964). Therefore, the results presented in Section IIa indicate that $r_g \simeq (2.4-4.0) \times 10^6$ s^{-1} cm^{-2} for the region of the galactic disk within 150 pc of the Sun. In steady state r_g must equal the hydrogen ionization rate.

This rate places an important constraint on the possible sources of ionizing radiation in the Solar neighborhood. Table 1 lists the ionizing fluxes per cm^2 of galactic disk of known sources of ionizing radiation averaged over a region within about 3 kpc of the Sun. The fluxes listed in Table 1 are upper limits on the amount of radiation that is actually available to ionize the diffuse interstellar medium, since some radiation may be absorbed by gas in the immediate vicinity of the source (e.g., to form a classical HII region) or may escape the galaxy entirely (X-rays). Each absorbed photon will produce approximately one hydrogen ionization in a nearly fully-ionized gas (Shull 1979). Only O-stars and perhaps planetary nebula nuclei have ionizing photon fluxes equal to or greater

TABLE 1

SOURCES OF IONIZING RADIATION

Source	Lyman Continuum Flux (10^6 photons s^{-1} per cm^2 of disk)	Reference
O stars	10–29	1, 2, 3
W-R stars	1.6	3
B stars	0.5–1	1, 2, 3
PN nuclei and white dwarfs	0.4–4	1, 4, 5
Supernovae	0.7	6, 7
QSOs	0.2	8, 9
Cosmic rays	0.008–0.08 [a]	10
X-rays ($h\nu \geq 0.1$ keV)	0.002	11

[a] Estimated number of hydrogen ionizations s^{-1} per cm^2 by cosmic rays ($\times 10^{-6}$).

REFERENCES.—(1) Terzian 1974. (2) Torres-Peimbert, Lazcano-Araujo, and Peimbert 1974. (3) Abbott 1982. (4) Salpeter 1978. (5) Hills 1973. (6) Chevalier 1974. (7) McKee and Ostriker 1977. (8) York 1982. (9) Paresce and Jakobsen 1980. (10) Spitzer and Jenkins 1975. (11) McCammon *et al.* 1983.

than the observed recombination rate. If O-stars are the primary source of the ionization, it remains to be determined how a significant fraction ($\gtrsim$ 10%) of the hydrogen ionizing radiation from these stars can escape the immediate vicinity of the stars and travel long distances through the interstellar medium. For example a line of sight through the galactic poles passes no closer than about 140 pc from the nearest O-star, ζ Oph (see Section IV). On the other hand, if the Lyman continuum flux from the central stars of planetary nebulae and hot white dwarf stars is near the high end of the range listed in Table 1 and if most of this radiation escapes the nebulae as has been suggested by Terzian (1974), then these older stars could be the primary source of the ionization for gas in the Solar neighborhood. Although B-stars, supernovae, and QSO's may not be able individually to account for the ionization rate, their combined effect ($< 2 \times 10^6$ s^{-1} cm^{-2}) could be significant if a large fraction of the ionizing radiation from each of these sources were absorbed in the diffuse interstellar medium. High resolution maps of the Hα background in regions which contain nearby planetary nebulae, hot white dwarfs, O and B stars may reveal surrounding ionization and thus may help to determine the importance of such sources for the ionization of the local interstellar gas (see Section IV).

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III. EVIDENCE FOR WARM, IONIZED GAS IN THE LOCAL INTERSTELLAR MEDIUM FROM PULSAR AND UV BACKSCATTER OBSERVATIONS

While optical emission line observations supply useful information about the temperature, fractional ionization, emission measure, and ionization rate within the diffuse, ionized component, they provide very little information about the precise location of the ionized gas. For example, all of the Hα background near the galactic poles could originate from gas at z-distances > 100 pc. It is even tempting to speculate that a possible decrease in the value of $I_\alpha \times \sin|b|$ for $|b| > 60°$ (Section IIa) could be explained by a deficiency of ionized gas within about 150 pc of the Sun, displaced perhaps by the hot, x-ray emitting gas. However, the dispersion measure of a nearby pulsar and backscattered solar UV radiation in the interplanetary medium provide strong evidence that a substantial amount of ionized gas is present within the local interstellar medium.

A distance of 127 ± 13 pc has been determined for PSR 0950+08 by Gwinn et al. (1984) using the parallax method. This pulsar has galactic coordinates $\ell = 228\overset{\circ}{.}9$, $b = +43°.7$ and a dispersion measure of 2.97 cm^{-3} pc. Therefore, along the line of sight to the pulsar the mean electron density $\langle n_e \rangle \simeq 0.023$ cm^{-3}, which is comparable to the mean electron density in the galactic disk (0.025 - 0.03 cm^{-3}) derived from much more distant pulsars (Weisberg, Rankin, and Borakoff 1980). It should also be noted that PSR 0950+08 is located in a quadrant in which the mean neutral hydrogen density appears to be < 0.01 cm^{-3} (Paresce 1984; Frisch and York 1983). If the ionized regions have an electron density $n_e \gtrsim 0.1$ cm^{-3} (see below), then they occupy $\lesssim$ 30 pc or $\lesssim$ 24% of the line of sight to PSR 0950+08. This suggests that a significant fraction of the local interstellar medium may be occupied by ionized hydrogen and that for some lines of sight the column density of H^+ may exceed that of $H°$. Salter, Lyne, and Anderson (1979) derived a distance of about 50 pc for PSR 1929+10, which has a dispersion measure of 3.2 cm^{-3} pc. If this distance is correct, then $\langle n_e \rangle \gtrsim 0.064$ cm^{-3} along the line to this pulsar ($\ell = 47°.4$, $b = -3°.9$). However, the validity of this distance is in some doubt (Backer and Sramek 1982).

Evidence that warm, ionized interstellar gas is present in the immediate vicinity of the Sun is provided by the hydrogen and helium Solar Lα backscatter results on gas flowing into the solar system. An analysis by Weller and Meier (1981) indicates that immediately outside the Solar system this interstellar gas has a temperature near 10^4 K, a neutral hydrogen density of 0.05 ± 0.01 cm^{-3} and a neutral helium density of 0.019 ± 0.008 cm^{-3}. They have suggested that the departure of the $H° : H_e^\circ$ ratio from its cosmic value can be explained if most ($\sim$ 75%) of the hydrogen is ionized. This interpretation is supported by the results of Bobroff, Nousek, and Garmire (1984), who concluded that the failure to detect HeII 304 Å emission from Capella could be explained if the hydrogen ionization fraction is greater than 40% along the line to the star (distance ≃ 14 pc). These results indicate that in the immediate vicinity

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of the Sun there exists a region of ionized gas with $n_e \approx 0.1$ cm^{-3} and $T \approx 10^4$ K. This gas therefore appears to be part of the same widespread, ionized component that is revealed by the Hα and pulsar data.

IV. O and B STAR HII REGIONS IN THE LOCAL ISM

In order to investigate the effect of O and B stars on the ionization of the local interstellar gas, Hα scans were obtained in the regions surrounding α Vir(B1 IV+B2 V), one of the nearest (d = 87 pc) early B stars, and ζ Oph (09 V), the nearest (d = 140 pc) O star. The observations reveal significant Hα intensity enhancements in the vicinity of each star. The ζ Oph HII region extends over an 8° x 12° region and has an emission measure of about 400 cm^{-6} pc and an electron density of 3.8 cm^{-3} near the star (Reynolds and Ogden 1982). The H^+ column density through the region is expected to be approximately 3×10^{20} cm^{-2}. The total hydrogen recombination rate within the region is estimated to be 1.8×10^{48} s^{-1}, which is close to the predicted Lyman continuum flux of an 09 V star (Panagia 1973). Thus most of the ionizing flux appears to be absorbed in the immediate vicinity (within 15 pc) of the star.

Twenty-nine Hα scans were obtained in the region surrounding α Vir. The resulting Hα intensities are displayed as a contour map in Figure 3. The HII region has an extent of 14° x 18° and an emission of about 8 cm^{-6} pc near

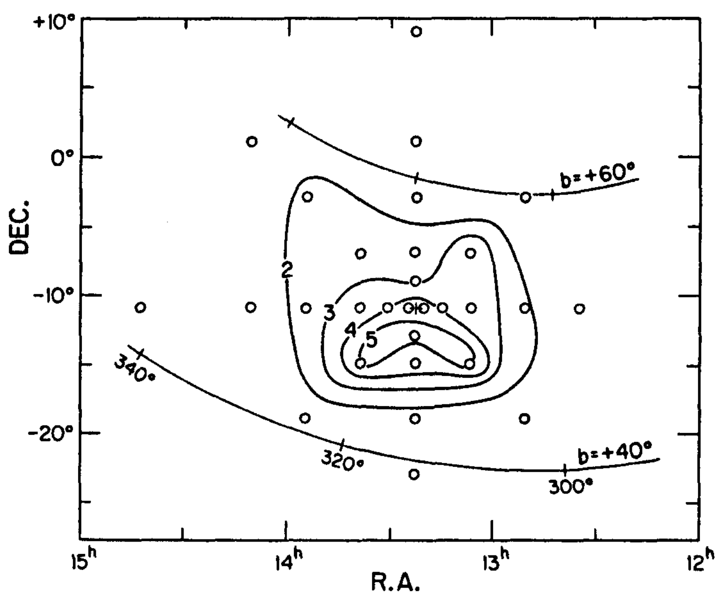

Fig. 3 - An Hα intensity contour map of the region surrounding α Vir. The open circles represent the location and field of view of the Hα scans. The contour values are in rayleighs (R). A galactic background Hα intensity of about 1.3 R near α Vir is indicated from the scans located outside the 2 R contour.

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the star (above a background emission measure of about 3 cm^{-6} pc). The region appears asymmetric with the brightest emission toward and south of α Vir. The radial velocity of the region is -6.1 ± 1.0 km s^{-1} with respect to the LSR (-9.8 ± 1.0 heliocentric), and the width of the Hα emission component is 21.2 ± 1.5 km s^{-1}. The electron density within this 25 pc diameter region is $\approx 0.58f^{-1/2}$ cm^{-3} (where f is the fraction of the HII region's volume occupied by ionized gas), and the H^+ column density through the region is thus $\approx 4 \times 10^{19} f^{1/2}$ cm^{-2}. The total hydrogen recombination rate within the HII region is estimated to be 2.0 ± 0.7 x 10^{46} s^{-1}, which is larger than the total Lyman continuum flux ($\simeq 5.8 \times 10^{45}$ s^{-1}) expected from a B1 IV + B2 V system (Panagia 1973). The factor of 3.5 discrepancy could be accounted for if α Vir had a slightly earlier spectral type (e.g., B0.7 IV instead of B1 IV) and/or its distance were less than 87 pc. In any case it appears that nearly all of the star's ionizing radiation is absorbed within its HII region and thus is not available to contribute to the ionization of the more diffuse component of the local interstellar medium.

The outer Hα intensity contour in Figure 3 is nearly coincident with a hole on the Berkeley 21-cm emission survey maps at radial velocities near 0 km s^{-1} (LSR). Also, the 21-cm maps centered near -6 km s^{-1} show the edge of a large HI feature just south of α Vir, where the Hα emission from the HII region is brightest. These coincidences suggest that the HII region surrounding α Vir is associated with the large, arch-like HI complex which extends up from the galactic plane at 0° to 20° longitude. The distance of this complex is therefore about 87 pc.

The Gum nebula, a 250 pc diameter region ionized by ζ Pup and γ Vel (Reynolds 1976a,b), and the equally large Orion-Eridanus shell ionized by the I Ori O-association (Reynolds and Ogden 1979) are two HII regions which may influence the local interstellar medium even though they are outside the arbitrarily defined 150 pc distance limit. Both regions have outer boundaries that appear to extend to within 300 pc of the Sun in the longitude interval 190° to 275°. This is the quadrant in which extremely low H° column densities (< 5 x 10^{18} cm^{-2}) are observed out to distances of at least 200 pc (e.g., Paresce 1984, and Figure 4 below). These two regions could be partially responsible for these low H° column densities if the boundaries of the regions extend somewhat closer to the Sun than their projection on the sky suggests, or if the regions are density bounded with a significant Lyman continuum flux escaping into the surrounding low density medium.

V. SUMMARY AND CONCLUSIONS

Observations of faint optical emission lines and pulsar dispersion measures provide evidence for a warm (10^4 K), ionized component of the interstellar medium which has an electron density of 0.1-0.2 cm^{-3}, and occupies $\approx$ 10% - 30% of the interstellar volume. The dispersion measure of a nearby pulsar, the observations of interstellar hydrogen and helium in the interplanetary medium, and UV observations toward Capella indicate that this ionized component is an important constituent of the local interstellar medium.

The source of this ionization has not yet been identified. However, the intensity of diffuse, galactic Hα emission at high galactic latitudes implies a hydrogen ionization rate in the vicinity of the Sun of $(2.4 - 4) \times 10^6\ s^{-1}$ per cm^2 of galactic disk. This places an important constraint on the possible sources of ionization. For example, this rate requires the equivalent Lyman continuum luminosity of one O9 V star or about 15 planetary nebula nuclei within a cylindrical region through the galactic disk of radius 150 pc centered on the Sun. The presence of an ionization

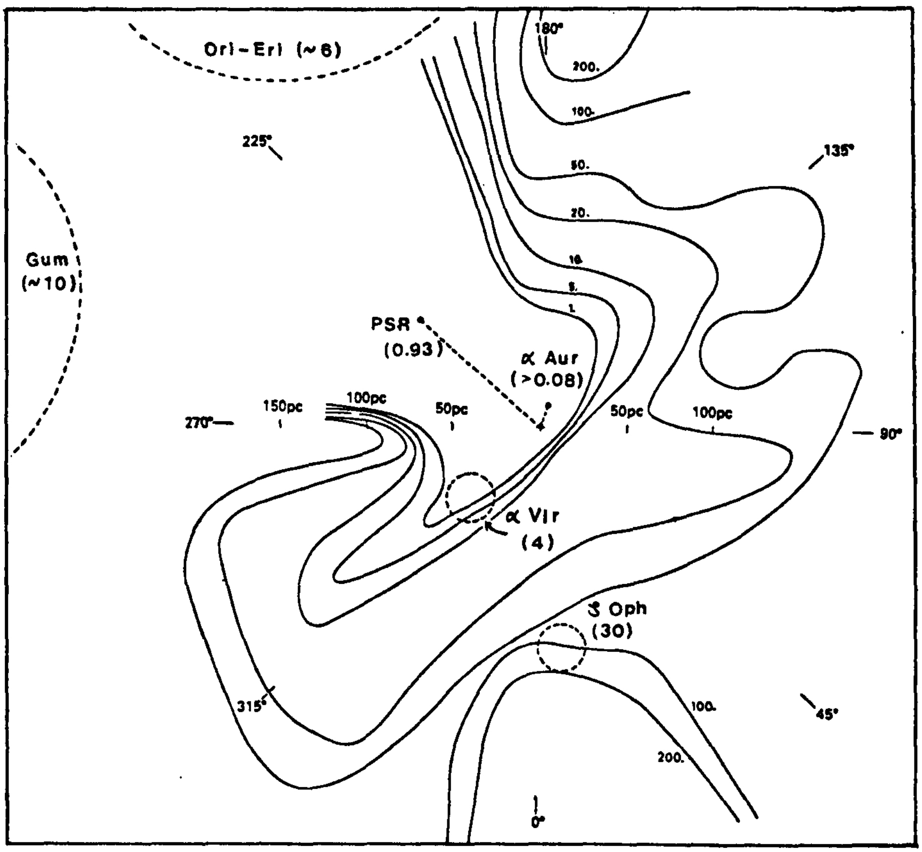

Fig. 4 - Observed regions of ionized gas in the local interstellar medium projected onto the galactic plane and superposed on a contour map of H° column densities by Paresce (1984). The lines of sight to PSR0950+08 and Capella (α Aur) are indicated by straight dotted lines. The size and location of HII regions are indicated by dotted circles. The number in parentheses denotes the H^+ column density in units of 10^{19} cm^{-2} along the line of sight to the star or pulsar or through the center of the HII region. The contours of H° column density (solid curves) are labeled from 1 to 200 units of 10^{19} cm^{-2}.

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bounded HII region surrounding ζ Oph, appears to eliminate this nearest O-star as an important source of ionization for the local gas. The combined ionizing flux from B-stars, supernova remnants, hot white dwarfs, and planetary nebula nuclei may account for the ionization provided that the Lyman continuum fluxes from these sources are near the upper end of the ranges listed in Table 1 and provided that a significant portion of the flux is not absorbed by gas immediately surrounding the sources. For example, the one local (distance of 87 pc) early B star that was investigated, α Vir, has an ionization bounded HII region which appears to be immersed in a large HI complex. The ionizing radiation extends no further than about 18 pc from α Vir. Figure 4 summarizes the locations (projected onto the galactic plane) and H^+ column densities of the regions of ionized gas revealed by the Hα, pulsar, and UV data. The regions are denoted by dashed lines and are superposed on a contour map of H° column densities in the local interstellar medium prepared by Paresce (1984). The number associated with each ionized region is the estimated H^+ column density through the region in units of 10^{19} cm^{-2}. Understanding the relationship between these warm, ionized regions and the neutral and the X-ray emitting regions should lead to a better understanding of the morphology and physics of the local interstellar medium.

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