IONIZED DISK/HALO GAS: INSIGHT FROM OPTICAL EMISSION LINES AND PULSAR DISPERSION MEASURES

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ABSTRACT. Warm ($\approx 10^4$ K), diffuse H^+ is a significant component of the interstellar medium within the Galactic disk and lower halo. This gas accounts for about one quarter of the interstellar atomic hydrogen, consumes a large fraction of the interstellar power budget, and appears to be the dominant state of interstellar matter 1 kpc above the midplane. The origin of this ionized gas is not yet established; however, of the known sources of ionization only O stars and perhaps supernovae produce enough power to balance the "cooling" rate of the gas. If O stars are the source of the ionization, then the interstellar HI, including the extended "Lockman layer", must have a morphology that allows about 14% of the Lyman continuum photons emitted by the stars to travel hundreds of parsecs within the Galactic disk and up into the lower halo.

1. INTRODUCTION

Pulsar dispersion measures and faint, diffuse optical line emission from the interstellar medium have firmly established the existence of a warm ($\approx 10^4$ K), ionized medium that is distributed throughout the Galactic disk and lower halo (see reviews by Kulkarni and Heiles 1986, 1987; and Reynolds 1989b). The dispersion measures have revealed directly the column densities and space averaged volume densities of the free electrons (and H^+), while the emission lines have provided information about the emission measures, temperature, ionization state, clumpiness, and kinematics of the gas. (In order to avoid confusion between this diffuse, ionized gas and the discrete regions of ionized gas traditionally referred to as "HII regions", the diffuse gas will be denoted as H^+ rather than HII.) The following is a review of some of the observations that have provided insight into the nature of the H^+ at large distances (up to ~ 1 kpc) above the Galactic midplane and its possible relationship to stars and gas near the plane.

2. THE SCALE HEIGHT AND COLUMN DENSITY OF THE H^+

The existence of a widespread, ionized component of the interstellar medium was established approximately two decades ago by observations of pulsar dispersion measures (Hewish et al. 1968) and

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faint optical line emission from the Galaxy (Reynolds 1971; Reynolds, Scherb, and Roesler 1973). The results revealed gas with a temperature T ≈ 6000-8000 K occupying a large fraction (f $\gtrsim$ 20%) of the interstellar volume. However, because the mean electron density of 0.03 cm^{-3} (e.g., Guelin 1974) amounted to only a few percent of the total midplane hydrogen density, and because probes of this gas tended to concentrate on its properties near the midplane, the total z-extent and column density of this component was not readily appreciated.

Recent discoveries of pulsars in globular clusters located far ($|z| \gtrsim$ 4 kpc) from the midplane have provided the opportunity to measure directly the total vertical extent and column density of the H^+. The vertical distribution of the gas is revealed in Figure 1, which is a plot of the component of the dispersion measure perpendicular to the Galactic disk against the distance $|z|$ from the midplane for pulsars with distances measured independently of their dispersion measures (e.g., Weisberg, Rankin, and Boriakoff 1987; Reynolds 1989a, and references therein; Frail 1989). The disk pulsars ($|z| \lesssim$ 300 pc) with distances ranging from 130 pc to more than 10 kpc from the sun sample a large area of the Galaxy near the solar circle.

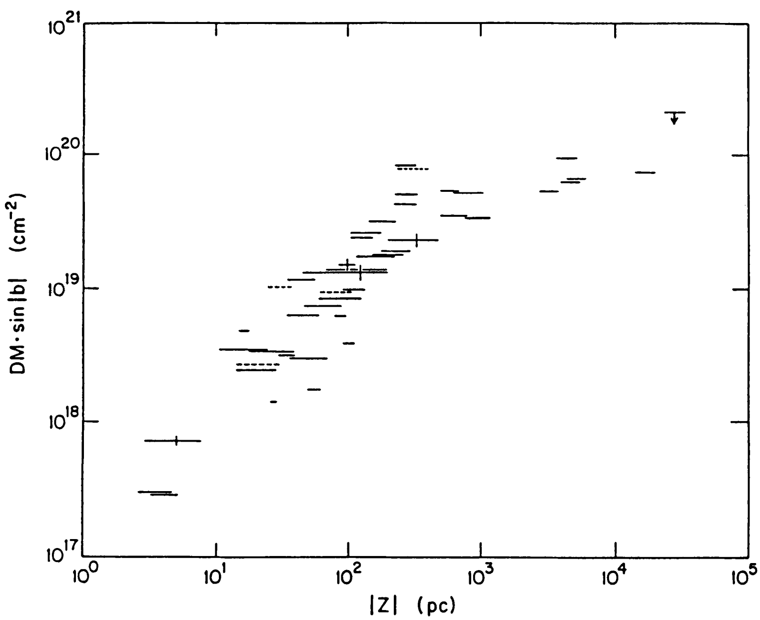

Fig. 1 - The component of the pulsar dispersion measure (i.e., the column density of H^+) perpendicular to the Galactic plane is plotted against distance $|z|$ from the midplane. Pulsars behind the Gum nebula are indicated by dashed lines; the pulsar in the LMC is indicated by an upper limit arrow.

Also included in Figure 1 are the globular cluster pulsars and the pulsar in the Large Magellanic Cloud (LMC). The data for these high $|z|$, non-disk pulsars are from Anderson et al. (1989 a,b,c,d, 1990); Biggs et al. (1990); D' Amico et al. (1990); Lyne et al. (1987, 1988); Manchester et al. (1989a,b); McCulloch et al. (1983); and Wolszczan et al. (1989a,b). The H^+ column density toward the LMC is plotted as an upper limit because of the possibility that some of it may be due to ionized gas within the LMC itself. On the other hand the fact that multiple pulsars in the same globular cluster have the same dispersion measure to within the measurement errors (e.g., Anderson et al. 1989a,b) implies that very little of the dispersion measure is associated with either the globular clusters or the pulsars themselves.

Figure 1 shows the extension of the H^+ layer up to $|z|$ heights of more than 1 kpc. Between $|z| \approx 0.8$ kpc and $|z| \approx 3$-5 kpc, for example, the mean column density increases from about 4.4×10^{19} cm^{-2} to 7.0×10^{19} cm^{-2}. The pulsars in the highest $|z|$ globular clusters and the LMC also reveal a "knee" in the distribution, implying a maximum extent $|z| < 4$ kpc and a total column density from the midplane approaching 10^{20} cm^{-2}. The mean value of DM $\cdot \sin|b|$ for the five highest $|z|$ pulsars (excluding the LMC) indicates an H^+ column density $N \approx 7.0$ $(+2.4,-1.5) \times 10^{19}$ cm^{-2}. This value is about 40% lower than that derived previously (Reynolds 1989a) because the high $|z|$ data set has increased and there have been changes in the reported values of some of the dispersion measures (e.g., for 47 Tuc; Manchester et al. 1989a).

The data in Figure 1 can be fitted well by a two-component electron density distribution given by

$$\langle n_e \rangle = 0.015 \exp(-|z|/70) + 0.025 \exp(-|z|/900) \text{ cm}^{-3}, \qquad (1)$$

where the first term represents, statistically, the contribution from discrete, classical HII regions near the midplane (see Lyne 1981; Manchester and Taylor 1981; Vivekanand and Narayan 1982; Harding and Harding 1982) and the second term represents the diffuse, extended component. This model is not strictly applicable to the data set in Figure 1 because the highest $|z|$ pulsars are all at high latitude and intersect no classical HII regions (i.e., have no contribution from the first term). However, this two-component fit clearly shows that diffuse ionized gas accounts for nearly all of the ionized gas in the Galactic disk, overwhelming the mass in the classical HII regions by 20 to 1.

Since the space averaged density of the extended, H^+ component at the midplane is $\langle n_e \rangle_o = 0.025 \pm 0.005$ cm^{-3} (Weisberg, Rankin, and Boriakoff 1980), its scale height H can be derived simply from the quotent $N/\langle n_e \rangle_o$, which has a value of 910 (+620, -320) pc. A similar analysis has recently been carried out by Lyne, Salucci, and Sciama (1990). A possible source of systematic error, which would tend to underestimate the value of H derived in this manner, is due to the fact that the high $|z|$ globular cluster pulsars used to determine N are all at high Galactic latitude and thus sample a relatively limited

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region of the disk near the sun, a cylinder of radius ≈ 1 kpc for a maximum z-height of ± 1 kpc, whereas the disk pulsars used to derive $\langle n_e \rangle_o$ are all at low latitudes and sample a much larger region of the disk, out to about 10 kpc from the sun. High latitude observations at 21 cm (Dickey and Lockman 1990; Lockman 1985) and at Hα (Reynolds 1984) indicate deficiencies of about a factor two in both the neutral hydrogen and the ionized hydrogen, respectively, near (< 1 kpc) the sun compared to the more distant regions of the disk sampled by lower latitude observations. Therefore, values of N and H that are not biased by this local deficiency could be as much as twice the values derived above.

An independent measurement of the scale height has been made from observations of the diffuse interstellar Hα emission associated with the Perseus spiral arm located at a distance of 3 kpc from the sun (Reynolds 1985a). The emission component associated with this spiral arm (identified by its -40 km s^{-1} radial velocity with respect to the LSR) extends more than 20° from the plane, corresponding to a $|z|$ height greater than 1 kpc. The rate of decrease in the Hα intensity with distance above the arm indicates an H^+ scale height of 600-1200 pc (Reynolds 1985a plus additional data; in preparation). As the accuracies of these two methods of determining H improve, it may become possible to compare the scale height above a spiral arm with the disk-wide average.

3. IMPLICATIONS OF THE LARGE SCALE HEIGHT

3.1 The H^+/HI Mass Ratio

The large scale height of the H^+ implies that most of this ionized gas is located well outside the traditional disk of the Galaxy. For H = 0.9 kpc, approximately 70% of the H^+ is located at $|z| > 300$ pc and half is at $|z| > 600$ pc. Therefore, although the average volume density of H^+ at the Galactic midplane is small compared to the HI, the H^+ nevertheless accounts for a relatively large fraction of the interstellar matter. The significance of this ionized component is illustrated in Table 1, which compares H^+ with HI column densities toward the five globular cluster pulsars that are located more than 3 kpc above the midplane (and thus sample nearly all the H^+). For these five "random", high latitude lines of sight the amount of ionized hydrogen ranges from 23% to 63% of the neutral hydrogen. In Figure 2 the average density of the H^+ as a function of distance $|z|$ above the midplane is compared with the average density of the HI (Dickey and Lockman 1990). The best-fit data for the H^+ and the HI thus suggest that at $|z| > 700$ pc the warm, ionized medium is the dominant state of the interstellar gas.

3.2 The Power Requirement and Source of the Ionization

The intensity of the Galactic Hα background at high latitudes provides a direct measure of the hydrogen recombination (and ionization) rate r_G in a cm^2 column perpendicular to the disk through

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TABLE 1

Comparisons of H^+ and H I column densities at high galactic latitude*

ℓ	b	N_{H^+} ($10^{20}cm^{-2}$)	N_{HI} ($10^{20}cm^{-2}$)	N_{H^+}/N_{HI}
4°	+47°	0.91	4.0	0.23
59	+41	0.94	1.5	0.63
65	-27	2.1	6.2	0.34
306	-45	0.77	2.75	0.28
333	+80	0.74	2.0	0.37

*Toward globular cluster pulsars with |z| distances > 3 kpc, which place them above > 90% of the H^+. Values for N_{H^+} are from Manchester et al. (1989a), Wolszczan et al. (1989a,b), and Anderson et al. (1989c,d). Values for N_{HI} are from McCammon et al. (1983) and Stark et al. (1989).

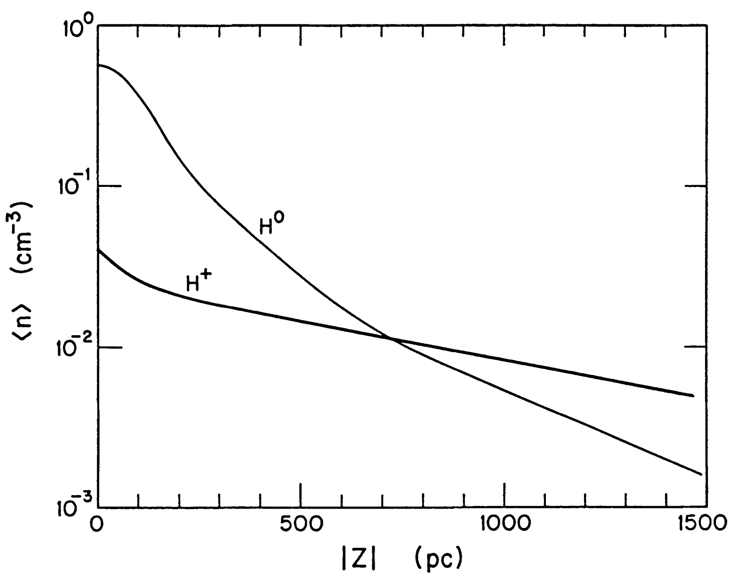

Fig. 2 - The best fit mean volume densities of H^+ from eq. 1 and H^o from Dickey and Lockman (1990) are plotted against distance |z| from the midplane.

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the relation

$$r_G = \frac{8\pi}{\varepsilon} I_\alpha \cdot \sin|b|, \qquad (2)$$

where ε is the average number of Hα photons produced per recombination (≈ 0.46; case B), I_α is the Hα intensity in units of photons $cm^{-2}s^{-1}sr^{-1}$, and b is the Galactic latitude of the Hα observation. An all sky average of the Hα data implies that $\langle r_G \rangle \approx 4 \times 10^6$ s^{-1} cm^{-2} for the region within 2-3 kpc of the sun (Reynolds 1984, 1987a). At 13.6 eV per ionization this rate corresponds to a power consumption of 1×10^{-4} ergs s^{-1} cm^{-2} just to keep the gas ionized. Approximately the same power is deduced independently from an examination of the pulsar dispersion measure data (Reynolds 1990b).

Of the known sources of ionization and heating within the Galactic disk, only the O stars, which produce 3×10^7 ionizing photons s^{-1} cm^{-2} (Abbott 1982), and supernovae, which inject about 1×10^{-4} ergs s^{-1} cm^{-2} (e.g., Abbott 1982), meet or surpass the power requirements of the H^+. Hot evolved stars (Panagia and Terzian 1984), cosmic rays (van Dishoeck and Black 1986), and the diffuse X-ray background (McCammon et al. 1983) fail to produce the required ionization by factors ranging from 20 to more than 100. Furthermore, Hα observations of an intergalactic HI cloud (Reynolds et al. 1986) and of high velocity clouds (Kutyrev and Reynolds 1989; Reynolds 1987b; Songaila, Bryant, and Cowie 1989), which probe the ionizing radiation field within and outside the Galactic halo, imply that at most 10% of the ionization rate can be due to radiation coming from outside the Galaxy. If supernovae are the source, they must be extremely ($\sim$ 100%) efficient at producing warm, ionized hydrogen, and if O stars are the source, then 14% of their Lyman continuum photons must somehow escape the immediate vicinities of the stars.

In the McKee and Ostriker (1977) model of the interstellar medium it is proposed that the diffuse H^+ is located in transition regions between the cold HI clouds and the hot, very low density "coronal" gas, and that it is photoionized by a very dilute Lyman continuum flux originating from lumunous stars and supernova remnants. However, this picture appears to be incompatible with the fact that most of the H^+ is located well above the thin layer of young stars and HI clouds that define the traditional disk of the Galaxy. The presence of the H^+ at high $|z|$ and along lines of sight that are far from ionizing stars (Reynolds 1990a), coupled with the existence of an opaque layer of HI that exends to high $|z|$ (Lockman 1984; Lockman, Hobbs, and Shull 1986), seem to require either the existence of some as yet unidentified source of ionization at high $|z|$ or a special morphology of the HI that allows the ionizing photons originating near the Galactic plane to travel a kiloparsec or more up into the lower halo (see Cox 1989; Bregman and Harrington 1986). For example, to account for the ionization at $|z| > 300$ pc with sources near the plane the flux of Lyman continuum photons flowing outward at $|z| = 300$ pc must be 2×10^6 photons cm^{-2} s^{-1}, or 7% of the total O star production rate. There is no known source of ionization with this strength located at such high $|z|$.

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4. THE TEMPERATURE AND IONIZATION STATE OF THE GAS

The power required to sustain ionized gas against cooling and hydrogen recombination losses has a minimum near 10^4 K and increases enormously for temperatures that are significantly hotter or colder (Reynolds 1990b). Since the power requirements of the gas are large relative to the power that is available from the known sources, it can be deduced independently of the emission line observations that nearly all of the ionized gas, even at high $|z|$, must be at a temperature near 10^4 K. The emission line data confine the temperature to the range 6000-20,000 K (Reynolds 1989b).

High [SII]λ6716/Hα and low [OIII]λ5007/Hα intensity ratios relative to those observed in O and B star HII regions imply ionization/excitation conditions in the diffuse, ionized gas that differ significantly from conditions within classical HII regions (Reynolds 1985b,c 1988). Models of photoionized gas suggest that the observed line intensity ratios could be the result of a dilute radiation field (e.g., Mathis 1986; J. Bland Hawthorne 1990). However, measurements of the [SII]/Hα intensity ratios in very faint (emission measures down to 5 cm^{-6} pc), extended (diameters up to 260 pc) HII regions that have been identified around O and early B stars have shown that the superposition of such regions cannot be the source of the diffuse background (Reynolds 1988). The observed tendency of the [SII]/Hα ratio to increase gradually with increasing dilution of the ionizing radiation suggests that, if the diffuse ionization consists of dilute, photoionized HII regions, then the regions must have an extremely low emission measure (EM < 1 cm^{-6} pc) and must be ionized by a Lyman continuum flux $F_{LC} < 6 \times 10^5$ photons $cm^{-2}s^{-1}$ (the equivalent of an unattenuated flux from a typical O star at a distance d > 400 pc). The [SII],[NII], and [OIII] intensities also suggest a low state of excitation with few ions present that require an ionization energy greater than about 23 eV. On the other hand the absence of [NI] and [OI] emission implies that the hydrogen is nearly fully ionized, with an ionization ratio $n(H^+)/n(H^\circ) > 2$ within the ionized regions (Reynolds 1989c). However, this result was obtained from observations at the Galactic equator, where the line intensities are bright enough to set useful limits. A probe of the hydrogen ionization ratio at higher latitudes will have to await the construction of more sensitive instrumention (see below).

5. CONCLUSIONS AND FUTURE DIRECTIONS

Warm, diffuse H^+ is a major component of the interstellar medium of our Galaxy, extending from the midplane into the lower Galactic halo, where it could be the dominant state of the interstellar gas. The existence of this component appears to have an important bearing upon the composition and topology of the interstellar medium and the principal processes of ionization and heating within the disk and halo. The diffuse H^+ also could contribute significantly to the total pressure at the midplane (Cox 1989) and have an important influence on the dynamics of hot (10^6 K) gas far above the plane (Heiles 1990). Furthermore, because the H^+ is a significant fraction of the

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interstellar matter, warm dust within it could be a non negligible source of IR continuum, and cosmic rays within it could produce a significant fraction of the diffuse γ-ray background, particularly at high Galactic latitudes (Bloemen 1989). The existence of the H^+ clearly needs to be taken into consideration in models of the interstellar medium and galactic halo and in the analysis of interstellar medium data.

While many of the basic properties of the H^+, such as its scale height, surface density, temperature, and power consumption, have been measured (though somewhat crudely), there is yet very little understanding about how this component fits together with the other components of the medium--the cold clouds, the warm HI, and the hot gas. The morphology of the H^+ is not known. Is this gas the ionized portion of the extended, warm HI (Lockman) layer, existing only where ionizing radiation from the disk leaks out between the clouds, like rays of sunlight through partial cloud cover (Cox 1989)? Or is this gas located on the inner surfaces of hot supernova created bubbles, chimneys, and worms? Also not understood is the support of the gas at high $|z|$ and, of course, the mechanism of ionization. Can O stars really be the source of the ionization 700 pc above the midplane, or are *in situ* sources required such as radiative cooling of hot gas (Martin and Bowyer 1990), a population of faint, hot stars at high $|z|$, or perhaps something exotic (e.g., Sciama 1990; Melott et al. 1989)?

It is possible that many of these questions will be answered in the near future. An extended H^+ component has recently been identified in the Sb galaxies NGC 891 (Rand, Kulkarni, and Hester 1990; Dettmar et al. 1989) and M31 (Walterbos and Braun 1990), and in some irregular galaxies (Hunter and Gallagher 1990). This has provided the opportunity to study the nature of this component from entirely new perspectives. Also, the continued discovery of pulsars in additional globular clusters around our Galaxy promises to improve column density and scale height determinations and probe the uniformity of the H^+ layer. Finally, the development of a more efficient spectrometer could soon make it possible to carry out a velocity resolved, all-sky survey of the optical line emission with an angular resolution comparable to that of the the 21 cm surveys (Reynolds et al. 1990). This new instrumentation would provide for the first time a clear, detailed picture of the distribution and kinematics of the H^+ within the interstellar medium and make possible the detection and study of additional, extremely faint diagnostic emission lines that probe the temperature and ionization conditions within the gas.

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