

## DIFFUSE IONIZED GAS IN SPIRAL GALAXIES AND THE DISK-HALO INTERACTION

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**Abstract.** Thick layers of warm, low density ionized hydrogen (i.e., the warm ionized medium or WIM) in spiral galaxies provide direct evidence for an interaction between the disk and halo. The wide-spread ionization implies that a significant fraction of the Lyman continuum photons from O stars, produced primarily in isolated star forming regions near the midplane and often surrounded by opaque clouds of neutral hydrogen, is somehow able to propagate large distances through the disk and into the halo. Moreover, even though O stars are the source of the ionization, the temperature and ionization state of the WIM differ significantly from what is observed in the classical O star H II regions. Therefore, the existence of the WIM and observations of its properties provide information about the structure of the interstellar medium and the transport of energy away from the midplane as well as place significant constraints on models.

### 1 Introduction

Forty-five years ago, Hoyle & Ellis (1963) proposed the existence of an extensive layer of warm ( $10^4$  K), low density ( $10^{-1} \text{ cm}^{-3}$ ) ionized hydrogen surrounding the plane of our Galaxy and having a power requirement comparable to the ionizing luminosity of the Galaxy's O and B stars. Their conclusion was based upon their discovery of a free-free absorption signature in the observations of the Galactic synchrotron background at frequencies below 10 MHz. However, the idea that a significant fraction of the Lyman continuum photons from the Galaxy's O stars could travel hundreds of parsecs throughout the disk conflicted with the traditional picture in which the interstellar neutral hydrogen confined the ionizing radiation to

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small volumes (i.e., “classical H II regions”) near the hot stars. Nevertheless, a few years later, the dispersion of radio signals from newly discovered pulsars (Hewish *et al.* 1968) plus the detection of faint optical emission lines from the diffuse interstellar medium (Reynolds 1971) firmly established warm ionized hydrogen as a major, wide-spread component of our Galaxy’s interstellar medium. But it was an additional two decades before deep H $\alpha$  imaging with CCDs began to reveal similar warm plasmas permeating the disks and halos of other galaxies (Rand *et al.* 1990; Dettmar 1990), establishing the WIM as not just a peculiarity of the Milky Way, but a common property of galaxy disks.

## 2 Basic Properties of the WIM

Though originally detected by radio techniques, subsequent developments in high-throughput Fabry-Perot spectroscopy and CCD imaging have demonstrated that the primary source of information about the distribution, kinematics, and other physical properties of the WIM is through the detection and study of its faint emission lines at optical wavelengths. Not surprisingly, the most detailed studies have been made for the Milky Way, particularly for the region within about 3 kpc of the sun. For example, the Wisconsin H $\alpha$  Mapper (WHAM) has been used to map the distribution and kinematics of the H $^+$  over the sky through the hydrogen recombination line and to probe the temperature and ionization conditions through the detection of weaker forbidden lines of trace ions and atoms (e.g., Haffner *et al.* 2003; Madsen *et al.* 2006).

The WHAM survey has revealed a complex morphology for the H $^+$ , with filaments and blobs extending to high Galactic latitudes and superposed on a smoother H $\alpha$  background that covers the sky. Comparisons of emission measures ( $\propto n^2$ ), derived from the H $\alpha$  intensity, with pulsar dispersion measures ( $\propto n$ ) indicate that the H $^+$  is clumped into regions having an average electron density  $n_e = 0.03 - 0.08 \text{ cm}^{-3}$  and filling a fraction  $f \approx 0.4 - 0.2$  of the volume within a 2000 – 3000 pc thick layer about the Galactic midplane. Half of the H $^+$  is located at heights  $|z| > 700 \text{ pc}$ . Within these ionized regions, the hydrogen is nearly fully ionized (H $^+$ /H  $> 0.9$ ) and has a temperature that is generally warmer than that of classical O star H II regions (see Sec. 4.2). The WIM accounts for 90% or more of the ionized hydrogen within the interstellar medium, and along lines of sight at high Galactic latitude, the column density of the H II is observed to range from 20% to 60% that of the H I. For details on how these parameters were derived, see the review by Haffner *et al.* (2009) and references therein.

## 3 O Stars as the Source of the Ionization

The low H $\alpha$  surface brightness of High Velocity Clouds (HVCs) in the halo of the Galaxy, approximately 1/10 that associated with the WIM (e.g., Tufte *et al.* 1998), implies that the source of the ionization of the WIM must be within the disk. In the solar neighborhood, the H-ionization rate needed to sustain the

WIM is about 1/7 that available from stellar Lyman continuum photons. In other galaxies, the fractions are found to scatter around a value closer to 1/2. Only O stars have this much ionizing power (e.g., Reynolds 1990). Studies of face-on galaxies in particular reveal that the total  $H\alpha$  luminosity of the diffuse ionized gas is on average approximately equal to that of the discrete, classical H II regions (Ferguson *et al.* 1996; Zurita *et al.* 2000; Oey *et al.* 2007). Moreover, across the faces of the galaxies, the  $H\alpha$  luminosity per unit area of the diffuse ionized gas tracks that of the discrete H II regions; that is, it correlates with the Lyman continuum production rate per unit area of a galaxy’s O stars (Zurita *et al.* 2000). Therefore, O stars are almost certainly the primary source of the WIM’s ionization.

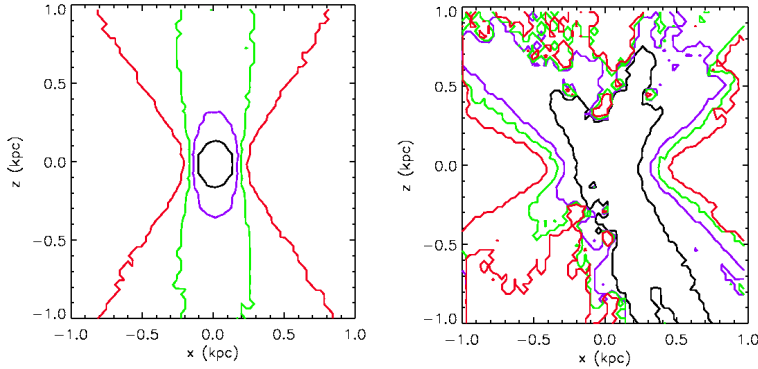
## 4 Challenges of O Star Ionization

The WIM is wide-spread throughout the disk and halo, and its emission line spectrum differs significantly from that of the higher density, classical H II regions immediately surrounding O stars. How can these observed properties be reconciled with O star ionization?

### 4.1 Pathways for the Ionizing Photons

To produce the extensive ionization that is observed, the stellar Lyman continuum photons must be able to travel hundreds of parsecs through the galactic disk. This places severe constraints on the distribution and column density of the H I within the galaxy. For example, at a distance of 200 pc from an O star (typical LC luminosity  $\approx 10^{49}$  photons  $s^{-1}$ ), the ionizing flux is about  $2 \times 10^6$  photons  $s^{-1} cm^{-2}$ . A balance of hydrogen ionizations and recombinations will show that an ionizing flux at this level will be totally absorbed by a cloud of density  $1 cm^{-3}$  or more having a column density of just  $10^{19} cm^{-2}$ .

Models suggest that a fractal H I distribution produced by interstellar turbulence (e.g., Elmegreen 1997; Wood *et al.* 2005) or large cavities (superbubbles/chimneys) created by clustered supernovae explosions (e.g., Norman & Ikeuchi 1989) may provide the necessary pathways. For example, 3D radiation transfer models by Wood *et al.* (2004) are illustrated in Figure 1 for “Strömgren Spheres” in density stratified gaseous disks. For the smooth density distribution, the H II region surrounding a single O star or a small cluster of O stars is confined to the midplane; however, when a portion (2/3 in this particular model) of the gas is hierarchically clumped, ionizing radiation from a single O star reaches more than 1 kpc from the disk. Not only models, but direct observations show that superbubbles also can be efficient conduits for ionizing photons. One such structure, shown in Figure 2, is the Perseus Superbubble, which extends above and below Cas OB6 (OC1 352), a cluster of nine O stars associated with the W4 H II region in the Perseus spiral arm.  $H\alpha$  emission from the outer boundary of this bubble indicates that 40% or more of the Lyman continuum luminosity of the O star cluster escapes the W4 H II region and ionizes gas out to  $30^\circ$  (1200 pc) or more from the stars (Reynolds *et al.* 2001). However, it is not clear which (if either) of



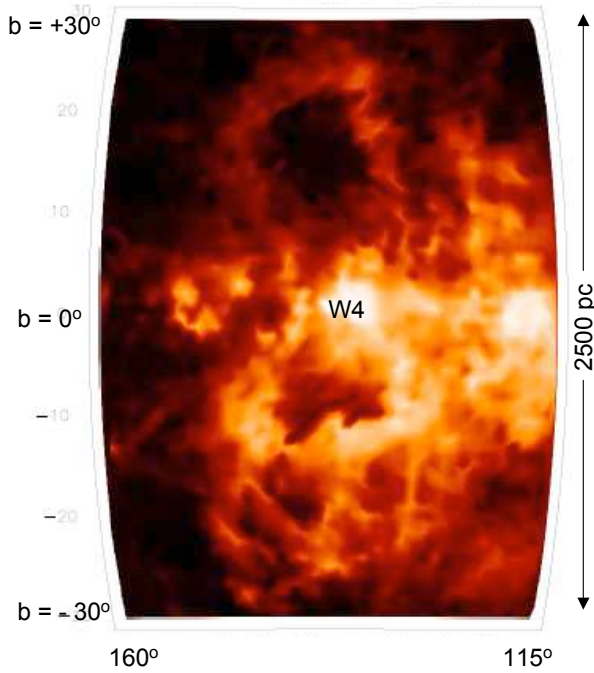
**Fig. 1.** Slices through the ionized region for point sources in smooth (left) and hierarchically clumped (right) density distributions. The mean vertical density structure for each simulation is that of a Dickey-Lockman disk. From the inner to outer contours the source luminosities (LC photons  $\text{s}^{-1}$ ) are  $10^{49}$ ,  $3 \times 10^{49}$ ,  $5 \times 10^{49}$  and  $10^{50}$  corresponding to a cluster of 1, 3, 5, and 10 O stars, respectively. A comparison of the contours in the smooth and clumpy models, shows that the clumped 3D density structure provides low density paths that allow ionizing photons to reach much larger distances from the source.

these avenues for the transport of ionizing radiation is correct. The morphology of the interstellar medium has not yet been characterized, and even though some superbubbles are observed to provide extended pathways, it is not known whether such cavities are sufficiently prevalent to account for the extensive  $\text{H}^+$ .

Finally, O stars alone do not appear to be sufficient to produce the diffuse ionization. A study of edge-on galaxies by Rossa & Dettmar (2003) has shown that the existence of an extended layer of  $\text{H}^+$  in a galaxy appears to require a star formation rate that exceeds a specific threshold (corresponding to an FIR surface brightness of  $1 - 3 \times 10^{40}$  ergs  $\text{s}^{-1}$  per  $\text{kpc}^2$  of galactic disk). Above this threshold, does the morphology of the interstellar medium change, allowing  $\approx 1/2$  of the ionizing radiation to escape the star formation regions?

#### 4.2 The Anomalous Emission Line Spectrum

A second challenge for O star ionization is the fact that the emission line spectrum of the WIM differs significantly from that of the classical  $\text{H II}$  regions that immediately surround O stars. One of the most interesting differences involves the  $[\text{N II}]\lambda 6583/\text{H}\alpha$  and  $[\text{S II}]\lambda 6716/\text{H}\alpha$  line intensity ratios. This is illustrated in Figure 3, which compares  $[\text{S II}]/\text{H}\alpha$  and  $[\text{N II}]/\text{H}\alpha$  in numerous high Galactic latitude WIM sightlines with the ratios toward classical  $\text{H II}$  regions. For the  $\text{H II}$  regions (Fig. 3a),  $[\text{N II}]/\text{H}\alpha$  is tightly clustered near 0.25, with  $[\text{S II}]/\text{H}\alpha \approx 0.1$ . The two exceptions are faint  $\text{H II}$  regions associated with hot, low mass evolved stars (see Madsen *et al.* 2006). On the other hand, for line ratios in directions



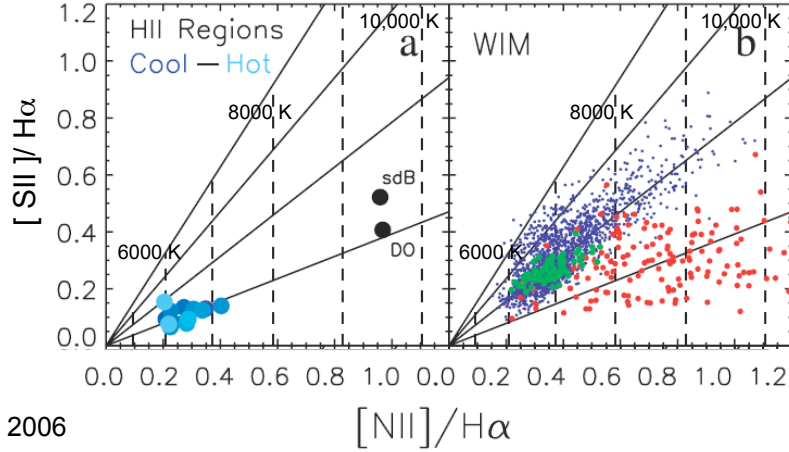
**Fig. 2.** A WHAM map of  $H\alpha$  emission from the Perseus Superbubble in the radial velocity interval  $-70 \text{ km s}^{-1} < V_{LSR} < -50 \text{ km s}^{-1}$ . The position of the W4 H II region associated with Cas OB6, the presumed source of the ionizing photons, is also indicated.

that sample the WIM (Fig. 3b), most of the  $[N \text{ II}]/H\alpha$  ratios and nearly all of the  $[S \text{ II}]/H\alpha$  ratios are significantly larger than those toward the classical H II regions. This result appears to be a characteristic of diffuse ionized gas, not just in our Galaxy, but in general (see, e.g., Rand 1998; Tüllmann & Dettmar 2000; Hoopes & Walterbos 2003). Discussions of other spectral differences can be found in Tüllmann & Dettmar 2000, Madsen *et al.* 2006, and Haffner *et al.* 2009.

There is strong evidence that these enhanced forbidden line intensities (relative to  $H\alpha$ ) are due primarily to higher temperatures in the WIM compared to the classical H II regions. The  $[N \text{ II}]\lambda 6583/H\alpha$  intensity ratio is given by

$$\frac{[N \text{ II}]}{H\alpha} = 1.62 \times 10^5 T_4^{0.4} e^{-2.18/T_4} \left( \frac{N^+}{N} \right) \left( \frac{N}{H} \right) \left( \frac{H^+}{H} \right)^{-1}, \quad (4.1)$$

where  $T_4$  is the electron temperature  $T$  in units of  $10^4$  K,  $N/H$  is the gas phase abundance of nitrogen relative to hydrogen, and  $N^+/N$  and  $H^+/H$  are the ionization fractions of N and H, respectively. Because  $H^+/H$  is nearly equal to  $N^+/N$  (both are near unity) in the ionized regions, local variations in  $[N \text{ II}]/H\alpha$  must be due essentially to variations in temperature (see discussion in Madsen *et al.*



**Fig. 3.** WHAM observations of  $[N II]/H\alpha$  versus  $[S II]/H\alpha$  toward classical OB star H II regions (left) and in directions that sample the WIM (right). The dashed vertical lines represent lines of constant temperature (from eq. 4.1) with  $5000 \text{ K} < T < 10\,000 \text{ K}$ . The four sloped solid lines represent, with increasing slope, values of constant  $S^+/S = 0.25, 0.50, 0.75$ , and  $1.0$  (eq. 4.2). For a more detailed description, see Madsen *et al.* 2006.

2006). This conclusion has been confirmed by observations of other emission line ratios, in particular,  $[O II]/H\alpha$  (Otte *et al.* 2002; Mierkiewicz *et al.* 2006) and  $[N II]\lambda 5755/[N II]\lambda 6583$  (Madsen *et al.* 2006).

Because the excitation energies for the  $[S II]\lambda 6716$  and  $[N II]\lambda 6583$  emission lines are nearly identical, the expression for  $[S II]/H\alpha$  has nearly the same dependence on  $T$  as the expression for  $[N II]/H\alpha$ , so that

$$\frac{[S II]}{[N II]} = 4.62 e^{0.04/T_4} \left( \frac{S^+}{S} \right) \left( \frac{S}{H} \right) \left[ \left( \frac{N^+}{N} \right) \left( \frac{N}{H} \right) \right]^{-1}. \quad (4.2)$$

However, due to its relatively low ionization potential (23.4 eV for  $S^+$  compared to 29.6 eV for  $N^+$ ),  $S^+$  is not necessarily the dominant ion within the ionized regions. As a result, observed variations in  $[S II]/[N II]$  are primarily a measure of variations of  $S^+/S$ .

From the above discussion, the data in Figure 3 can be interpreted as measurements of  $T$  and  $S^+/S$  within the ionized regions. The data show that not only is the WIM generally warmer than the H II regions, but that within the WIM there are substantial variations in both the temperature and ionization state from one line of sight to the next.

## 5 Why is the WIM Warmer than the Classical H II Regions?

The variations in  $S^+/S$  could be a measure of differences in the ionization parameter, that is, the  $S^+$ -ionizing photon density to electron density ratio, within the ionized regions (Mathis 1986). The significant variations in temperature are more difficult to understand. Photoionization models suggest that some temperature increases could result from the hardening of the ionizing spectrum as the radiation passes through density bounded H II regions before reaching the more distant WIM (Wood & Mathis 2004; Wood *et al.* 2005). However, this mechanism does not explain the highest values of  $[N II]/H\alpha$ , i.e., the large range in temperatures that is observed. To produce the higher temperatures, an additional, non-ionizing source of heat must be added (Wood & Mathis 2004).

One clue about the nature of this supplemental heating is the observed strong anticorrelation between  $[N II]/H\alpha$  (temperature) and the  $H\alpha$  intensity (gas density). This anticorrelation is apparent in observations of our Galaxy (e.g., Madsen *et al.* 2006) and other galaxies, not just with increasing distance  $|z|$  from the midplane, but also in observations at constant  $|z|$  (e.g., Rand 1998). This behavior could be explained if there were a heat source with a heating rate per unit volume proportional to the first power of the density, or did not depend upon density at all. Then, at sufficiently low densities, such a source would dominate over photoionization heating (which is proportional to  $n^2$ ), producing the observed inverse relationship between temperature and density (see Reynolds *et al.* 1999). The required heating rate is  $\sim 10^{-26} - 10^{-25}$  erg s $^{-1}$  per H $^+$ , or  $\sim 10^{-27}$  erg s $^{-1}$  cm $^{-3}$  (Wood & Mathis 2004; Reynolds *et al.* 1999). Possible sources include photoelectric heating by dust (Weingartner & Draine 2001), dissipation of turbulence (Minter & Spangler 1997), and magnetic reconnection (Raymond 1992).

## 6 Conclusions

The thick layers of warm, low density H $^+$  in spiral galaxies contain clues about the structure of the interstellar medium and the transport of energy away from regions of star formation at the midplane. Some progress has been made in understanding this gas, but many fundamental questions remain: How does the ionizing radiation propagate through the disk? Why is the H $^+$  layer so thick? What is the distribution of the WIM within the interstellar medium? What is its relationship to the other phases of the medium? What is the source of the elevated temperatures in the WIM? Comparisons of the observed distribution, motions, and line ratios of the WIM with predictions of models have begun to address some of these questions (e.g., Hill *et al.* 2008; Wood & Mathis 2004). Perhaps a next step is to compare the observations to more sophisticated multi-phase, dynamical models that included sources of heating and ionization with 3D radiation transfer. The observations would constrain model parameters, and the models could predict properties of the gas to guide future observations.

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