MEASUREMENTS OF He I $\lambda$5876 RECOMBINATION-LINE RADIATION FROM THE DIFFUSE, WARM IONIZED MEDIUM IN IRREGULAR GALAXIES

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Received 1996 October 22; accepted 1997 February 11

ABSTRACT

We present long-slit optical spectroscopy of three high surface brightness Magellanic irregular galaxies. This paper draws attention to our detection of He I $\lambda$5876 line emission from the ionized gas outside the H II regions or the warm ionized phase of the interstellar medium. We measure a mean reddening-corrected intensity ratio of He I $\lambda$5876/H$\alpha$ $\approx$ 0.041 independent of spatial location. This ratio is much higher than that measured in the diffuse, warm ionized interstellar medium of the Milky Way (Reynolds & Tufte).

The high value of He I $\lambda$5876/H$\alpha$ implies the helium ionization fraction is approximately equal to the hydrogen ionization fraction in the diffuse ionized gas (DIG). If the DIG is powered by young stars, then stars hotter than 40,000 K must contribute to the Lyman-continuum radiation reaching the DIG. Since optical and ultraviolet spectra confirm the presence of such massive stars in these galaxies, stellar photoionization remains the most likely power source. The contrast with the low helium ionization in the Galactic DIG, however, is intriguing and provides strong evidence that the physical state of the DIG, not just its presence, varies among galaxies.

Subject headings: galaxies: individual (NGC 1569, NGC 4214, NGC 4449) — galaxies: irregular — galaxies: ISM — ISM: structure

1. INTRODUCTION

Warm, diffuse ionized gas (DIG) comprises a significant fraction of the mass and volume of the interstellar medium (ISM) in galaxies. In the Milky Way, this component is sometimes referred to as the Reynolds Layer and has a scale height $\sim$ 1 kpc (Reynolds 1991). Galactic O and B stars supply enough power to keep it ionized (Reynolds 1984), and the only conundrum had been how the Lyman-continuum radiation from O and B stars, with scale height $\sim$ 100 pc, can reach the DIG. The close correlation between the presence of extended, diffuse ionized gas in other galaxies and various tracers of massive star formation seemed to place the OB-star photoionization hypothesis on relatively firm ground (Hunter & Gallagher 1990; Dettmar 1992; Rand 1996b).

The massive-star photoionization picture has been challenged, however, by new measurements of the He ionization fraction in the Galactic DIG. First, a search for He I $\lambda$5876 recombination line emission from the local DIG set an upper limit on the He I $\lambda$5876/H$\alpha$ intensity ratio of 0.011 (Reynolds & Tufte 1995). For a He/H abundance ratio of 1:10 by number in the DIG, the implied relative ionization fraction is $\chi$(He)/$\chi$(H) $\equiv$ [n(He$^+$)/n(He)]/([n(H$^+$)/n(H)]] $\leq$ 0.25. This high neutral fraction of He implies that the interstellar radiation field is softer than that expected from the Galactic O star population in the solar neighborhood (Reynolds & Tufte 1984). Further work has shown that this curiosity is not confined to the solar neighborhood. Heiles et al. (1996) observed hundreds of positions toward the Galactic center at ~1.5 GHz. The relative strengths of the H and He radio recombination lines from the quasi-vertical filaments of ionized gas known as "worms" indicate a relative ionization fraction $\chi$(He)/$\chi$(H) $\leq$ 0.13 there, which implies that stars more massive than about 39 $M_\odot$ must not contribute to the ionizing continuum (Heiles et al. 1996). To meet the measured ionization rate in the Galaxy, however, the global star formation rate would need to be significantly higher than previously estimated (Heiles et al. 1996).

Nearby galaxies provide an opportunity to examine the relationship between the properties of the DIG and the stellar content of a galaxy. Among normal galaxies, Magellanic irregular galaxies have the most intense star formation in terms of both the number of H II regions per unit luminosity and the ionizing luminosity of the brightest H II region (Kennicutt, Edgar, & Hodge 1989). To investigate the ionization state of He in the warm ionized phase of the ISM of such galaxies, we selected three irregular galaxies with copious amounts of diffuse and filamentary H$\alpha$ emission from a larger sample of dwarf galaxies (Martin 1996). In this paper, we report measurements of the He I $\lambda$5876 line emission in the DIG from long-slit spectra. A more detailed discussion of the emission-line spectra and their implications for the excitation of the DIG can be found in Martin (1997).

2. MEASUREMENTS OF He I $\lambda$5876 LINE EMISSION

2.1. The Galaxies

The galaxies NGC 4214, NGC 1569, and NGC 4449 were selected for their star formation activity, proximity, and prominence of ionized gas beyond the H II regions. They are gas rich and have absolute blue luminosities between those of the Small Magellanic Cloud and Large Magellanic Cloud. Table 1 compares some relevant properties of the observed galaxies to the Milky Way. Their current rates of massive star formation, 0.25 and 0.50 $M_\odot$ yr$^{-1}$, are only ~5 times lower than that in the Milky Way but, unlike our Galaxy, are equal to or a few times larger than the past

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average rate of star formation in each galaxy (Kennicutt 1983; Kennicutt, Tamblyn, & Congdon 1994). Spatial and temporal fluctuations in the star formation rate have clearly occurred. For example, the northern region of NGC 4449 is younger than the main bar (see, e.g., Hill et al. 1994), and NGC 1569 is emerging from a major burst of star formation (Israel & de Bruyn 1988; Waller 1991; Heckman et al. 1995). Their lower oxygen abundance, O/H $\lesssim 0.20$ (O/H)$_{\odot}$, is also consistent with a much lower total amount of star formation in the past (Martin 1997).

### 2.2. Observations and Reductions

We obtained long-slit spectra at 11 positions across these galaxies at the Multiple Mirror Telescope during the period 1994 February to 1995 March. The Blue Channel spectrograph was used with a 500 grooves per millimeter grating, a Loral 3k $\times$ 1k CCD detector, and a 1" by 3" slit. This setup produced wavelength coverage from 3700 to 6800 Å and a spectral resolution of 4–5 Å at H$\alpha$. Slit positions were chosen in advance to sample both H II regions and extended, diffuse emission and were required to be close to the parallactic angle at the time of observation. Their exact locations are illustrated in Martin (1997), where additional details about the observations and reductions can be found. The spectra reach a surface brightness $\sim 2.5 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, which corresponds to an emission measure of 14 at $T_e = 10^4$ K.

The He I $\lambda5876$ line is clearly visible along a substantial length of the slit in the raw data. We divided this region into 3" apertures and extracted a series of one-dimensional spectra from the sky-subtracted and continuum-subtracted frames as described by Martin (1997). Fortunately, the recessional velocities of these galaxies are less than 300 km s$^{-1}$, so the line is cleanly separated from the bright night sky emission at Na I $\lambda5890, 96$. Our continuum template does not include line emission, so stellar absorption and emission lines are present in the continuum-subtracted frames. The correction to the nebular He I $\lambda5876$ emission will be significant only where the emission line is weak relative to the continuum, and very little continuum emission underlies most of the low surface brightness DIG in our spectra. Measurements from our spectra of the H II regions, however, do show a slight trend for the He I $\lambda5876$/H$\alpha$ ratio to decrease as the emission-line equivalent width decreases. The slope of this relation places an upper limit of 0.3 Å on the equivalent width of the underlying He I $\lambda5876$ absorption there.

The He I $\lambda5876$, H$\alpha$, and H$\beta$ fluxes were measured from these spectra using the “splot” task in IRAF. The He I $\lambda5876$/H$\alpha$ ratio was corrected for reddening using the extinction curve of Miller & Matthews (1972) and the logarithmic extinction at H$\beta$, $c$(H$\beta$). We derived $c$(H$\beta$) from the Balmer decrement assuming a constant underlying stellar absorption equivalent width of 2 Å $\pm$ 2 Å and an electron temperature of 10,000 K. We found little variation of $c$(H$\beta$) with position along the slit, so the mean value was adopted at each position angle. An uncertainty, $dc$(H$\beta$) in Table 1, was assigned based on the variation in $c$(H$\beta$) along the slit or the formal error, whichever was larger. This term dominates the error estimates of the He I $\lambda5876$/H$\alpha$ intensity ratio. Only a portion of the data was obtained under photometric conditions, but the relative flux calibration for all observations is good to $\sim$2%, based on observations of multiple standard stars (Massey et al. 1988).

### 2.3. Results

Figure 1a shows the reddening-corrected ratio of the He I $\lambda5876$ to H$\alpha$ emission-line intensity as a function of H$\alpha$ surface brightness along the 11 slit positions. The H$\alpha$ surface brightness is closely correlated with the angular distance from the nearest giant H II region along our slit positions (see Fig. 2) and can therefore represent the relative distance of the aperture from the ionizing cluster. The average He I $\lambda5876$/H$\alpha$ intensity ratio is 0.041, the lowest value is 0.028, and the highest value is 0.058. Comparison with Figure 1b shows that only NGC 1569 and position 3 in NGC 4449 (PA = 137°2) have large corrections for reddening. Across each galaxy, we find no systematic variation in He I $\lambda5876$/H$\alpha$ despite a decline in H$\alpha$ surface brightness by a factor of $\sim 100$.

The gradients in other diagnostic line ratios measured from the same spectra emphasize the remarkable uniformity...
of He I λ5876/Hα. Figure 2 demonstrates the contrast along position 2 in NGC 1569. Across the region where He I λ5876/Hα is measured, the [S II] λ6717, 31/Hα, [N II] λ6583/Hα, and [O I] λ6300/Hα ratios increase by factors of a few, while [O III] λ5007/Hβ decreases by a similar factor. This spectral change is typical of the DIG in low-metallicity galaxies (Martin 1997). Martin (1997) studied these spectral changes using photoionization models and found the gradients in the line ratios primarily reflect a gradient in the relative density of ionizing photons to gas. The ionization parameter is inferred to fall by a factor ≳ 10 over the region where we have measured a constant He I λ5876/Hα ratio (Table 2).

Under normal conditions, the relative intensity of He I λ5876/Hα can be predicted from the effective recombination coefficients of He and H. At $T = 10^4$ K and $n = 100$ cm$^{-3}$, the recombination coefficients for He and H from Brocklehurst (1972) and Hummer & Storey (1987), respectively, yield an emissivity ratio

$$\frac{E_{5876}}{E_{H\alpha}} = 0.470 \frac{\chi(\text{He})}{\chi(\text{H})},$$

where He/H is the abundance ratio by number. (The revised emissivities of Smits [1996] would raise the coefficient in eq. [1] by 0.004, while raising the temperature to $1.2 \times 10^4$ K would lower it by 0.004.) Assuming that the abundance ratio of He/H by number is $\lesssim 0.1$ and comparing the measured intensity ratios with equation (1), we see that $\chi(\text{He})/\chi(\text{H}) \approx 1$.

If we adopt $\chi(\text{He})/\chi(\text{H}) = 1$, then the mean ionic abundance of He$^+$ relative to H$^+$ is He$^+$/H$^+ = \bar{y}^+ = 0.087$, which is consistent with the He/H ratio predicted by the He versus O regression relation of Pagel et al. (1992) for the oxygen abundance, log (O/H) = $-3.69 \pm 0.07$, in NGC 4449. The slightly lower O/H ratios in Table 1 for NGC 1569 and NGC 4214 are not unusual for an abundance ratio He/H $\approx 0.087$. For example, within the O/H range of our three irregular galaxies, Table 15 of Pagel et al. (1992) contains H II regions with $y^+$ varying from 0.081 to 0.090. Also, Kobulnicky & Skillman (1996) find variations in O/H

![Figure 1](image1.png)

**Figure 1.**—Dependence of the He I λ5876/Hα intensity ratio on Hα surface brightness (a) without corrections for reddening and (b) with the dereddened line ratios and surface brightnesses. The surface brightness at the positions represented by large symbols is in units of ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. The small symbols denote nonphotometric data and could be misplaced by as much as $\pm 0.5$ dex in surface brightness.

![Figure 2](image2.png)

**Figure 2.**—Changing emission-line spectrum across NGC 1569, PA = 32°4. Top Left: Hα and continuum surface brightness vs. separation from the brightest H II region along the slit. Counterclockwise from top left, the emission-line ratios are [S II] λ6717, 31/Hα; He I λ5876/Hα; [N II] λ6583/Hα; [O I] λ6300/Hα; and [O III] λ5007/Hβ.
within NGC 4214 as large as ~45%, whereas He⁺/H⁺ changes by only ~6% among the same regions.

3. DISCUSSION: THE SOURCE OF IONIZING PHOTONS

Our spectra also show evidence for emission from gas excited by 60–100 km s⁻¹ shocks (Martin 1997). These results are discussed in depth in a separate paper, and we comment here only on the sensitivity of He I λ5876/Hα to shock velocity. In the models of Shull & McKee (1979), He I λ5876 emission is negligible until shock speeds reach 80 km s⁻¹; even then, the He I λ5876/Hα intensity ratio is only 0.005. Increasing the shock speed to 100 km s⁻¹, however, raises He I λ5876/Hα to 0.047. It is possible then that shocks may contribute to the high values in Figure 1. However, we suspect the correction is not large because (1) shock-excited gas typically contributes ≤20–30% of the emission, and (2) while the relative contribution from shocked gas grows with distance from the star forming regions, the He I λ5876/Hα ratio exhibits no systematic variation (Fig. 1). The relative amounts of He and H ionization in the DIG are therefore a measure of the hardness of the Lyman-continuum radiation ionizing the DIG.

3.1. The Lyman Continuum

Figure 3 illustrates the dependence of the He I λ5876/Hα intensity ratio of an H II region on the stellar luminosity of He-ionizing photons relative to H-ionizing photons, Q(He)/Q(H). The ratio He I λ5876/Hα increases linearly with Q(He)/Q(H) until H begins to compete for hv > 24.6 eV photons and then saturates at a constant value when the volume-averaged χ(He) ≈ χ(H) ≈ 1 (Osterbrock 1989). In Figure 3, the arrow illustrates the analytic relation for the linear rise, and the turnover is illustrated by the line ratios of the model nebula ionized by stars with Q(He)/Q(H) ≈ He/H. Since the mean He I λ5876/Hα = 0.041 in these irregular galaxies, we see from Figure 3 that the Lyman continuum must have Q(He)/Q(H) greater than 0.12, and this mean intersects the relation for the He/H = 0.85 models at Q(He)/Q(H) ≈ 0.25. The He I λ5876/Hα intensity ratio is, however, not very sensitive to the spectral hardness at temperatures hotter than Tₚ = 40,000 K.

The equivalent stellar mass depends on the spectral metallicity, the stellar atmospheres chosen, and the adopted grid of evolutionary models. To illustrate the sensitivity to these assumptions, four mass scales are shown at the top of Figure 3. For example, using the most recent atmospheric models from Schaefer & de Koter (1996) and the evolutionary models of Schaller et al. (1992) as parameterized by Vaytet, Garmany, & Shull (1996), the spectrum is harder than that of a ~30 M☉ solar metallicity star (scale c). If we use the same models as Heiles et al. (1996) for a direct comparison with their analysis of the Milky Way DIG, the minimum mass star that has a spectral hardness consistent with the He ionization of the DIG in the irregular galaxies is ~44 M☉.

Of course many stars contribute to the ionization of the DIG, and the Q(He)/Q(H) ratio of the ensemble will be less than that emerging from the most massive star. The 0.25 Z☉ evolutionary synthesis models of Leitherer & Heckman (1995), for example, predict a spectral hardness Q(He)/Q(H) = 0.23 and Q(He)/Q(H) ≈ 0.07 from stellar populations continuously forming stars with a Salpeter initial mass function (IMF) and upper mass limits of mₘₚ = 100 M☉ and 30 M☉, respectively. The ratio can be considerably higher, Q(He)/Q(H) ≈ 0.32, if the burst is less than a few Myr old. Hence, 30 M☉ is only a lower limit on the upper mass cutoff of the stellar population ionizing the DIG.

3.1.1. Direct Evidence for Massive Stars

Optical and ultraviolet spectra provide direct evidence for massive stars in all three galaxies. Several H II regions in NGC 4214 show strong, broad He II λ4686 and C IV λ5808 emission lines from WN and WC stars (Sargent & Filippenko 1991). Our spectra also reveal both of these features in several H II regions in NGC 4449 as well as broad λ4686 in NGC 1569 (see Drissen, Roy, & Moffat 1993; Gonzalez-Delgado et al. 1997). These Wolf-Rayet stars are thought to
be the short-lived descendants of the most massive O stars (\(M \geq 35\ M_{\odot}\)) (Conti et al. 1983; Humphreys, Nichols, & Massey 1985). Spectral synthesis modeling of the ultraviolet continuum from the most prominent cluster in NGC 4214 suggests several hundred O stars are present in addition to the \(~30\) Wolf-Rayet stars (Leitherer et al. 1996). Hence, the hard interstellar Lyman continuum in these irregular galaxies is not unexpected. It is, rather, the contrast between the spectral energy distribution of the photons ionizing the DIG in irregular galaxies and the Milky Way that is of interest.

3.2. The Morphology Problem

The morphology problem in the Galaxy, again, is how the ionizing photons from O and B stars, scale height \(~100\) pc, can reach the DIG when their absorption mean free path is only 0.5 (0.1 cm \(^{-1}/n_\text{H}\)) pc at 1 rydberg (see, e.g., Dove & Shull 1994; Miller & Cox 1993). In irregular galaxies, the DIG also extends over a kiloparsec from the main star-forming regions. And, in both environments, spectra of DIG regions \(~100\) times fainter than the discrete H II regions (Reynolds 1991; Reynolds & Tufte 1995) indicate the ionization parameter is very low (Dömgorgen & Mathis 1994; Martin 1997). These conditions are consistent with a distant source of ionizing photons. However, the spectroscopic signature of gas photoionized by a distant association is nearly indistinguishable from that of a dilute H II region, and it is worthwhile to reexamine the possibility that the DIG in irregular galaxies might be ionized locally and the radiation transport problem avoided.

About 80% of the ultraviolet light from starburst regions is believed to come from massive stars between and beyond the young clusters (Meurer et al. 1995). However, since most studies of the individual massive stars in these galaxies have focused on star clusters, it is not clear at present how far from the clusters the young field population might extend (see Gallagher et al. 1996). In extreme environments, such as the outflow extending several kiloparsecs above the disk of NGC 1569 (Heckman et al. 1995), it seems highly unlikely that the DIG is ionized by nearby stars. In addition to the difficulties of forming stars in the tenuous outflow, the dramatic increase in Hz equivalent width with radius (see Waller 1991, Fig. 5a) is most naturally explained by photons escaping the starburst region and/or shock excitation. However, the situation is much less clear a few hundred parsecs to 1.5 kpc away from the clusters—the type of environment well sampled by our spectra, and it is here that we consider whether the DIG could be comprised solely of low surface brightness H II regions excited by a young field population.

3.2.1. Is Local Ionization Consistent with the Spectral Gradient?

Such a question is hard to answer definitively without observing the presence/absence of an extended population of hot stars. However, some insight can be obtained by investigating whether such an assertion is compatible with the observed spectral gradient. For the purpose of illustration, we take the viewpoint that all the H II regions are ionization bounded and that the radial gradients in Hz surface brightness (\(\Sigma\)) and ionization parameter (\(U\)) result from changes in the H II region population. The simplest possible geometry for the H II regions surrounding an isolated star or cluster is a homogeneous Strömgren sphere, a fraction \(\epsilon\) of which is filled with gas clouds of density \(n\). The nebular ionization parameter will scale as

\[ U \propto Q^{1/3} n^{1/3} \epsilon^{2/3} , \]

where \(Q\) is the ionizing luminosity of the star or cluster, and the average Hz surface brightness of the nebulae will scale as

\[ \Sigma \propto Q^{1/3} n^{4/3} \epsilon^{2/3} . \]

These scaling relations are reasonably robust with respect to the local nebular geometry. For example, if the circumstellar medium surrounding each massive star has been swept into a thin shell of thickness \(\Delta R = (4/3\pi n^3 R^3)/(4\pi R^3 4n_\text{H}) = 1/12R\), the same scaling arguments would continue to hold under the assumption that the nebulae remain ionization bounded. The absolute surface brightness and ionization parameter of the shell and filled sphere models would of course differ, but they scale in the same manner with \(Q\), \(n\), and \(\epsilon\).

From equations (2) and (3), we see that a large-scale gradient in the ambient gas density is insufficient by itself to explain the spectral gradient. Using equation (2), a smooth change in gas density of a factor of \(10^3\) between the giant H II regions and the DIG could produce the observed drop, a factor of 10, in ionization parameter. Equation (3) predicts the surface brightness of the low-density nebulae would,
however, be a factor of $10^4$ times fainter than the giant H II regions—a much greater contrast than observed.

In principle, a decrease in the luminosity of the star clusters with galactic radius could produce a gradient in the nebular spectrum and alleviate the need to transport ionizing photons large distances. The 3 order of magnitude drop in $Q$ required to reduce the ionization parameter by a factor of 10 would be similar to the difference in ionizing luminosity between a giant H II region and a single hot star, so individual, isolated stars would be ionizing the lowest surface brightness DIG. Although the accompanying reduction in Hz surface brightness is only a factor of 10, the surface brightness could be decreased further to the observed factor of 100 by a mild density gradient in the ambient medium without decreasing the ionization parameter much beyond the measured range. Ionization of the DIG by a population of field O and B stars cannot, therefore, be ruled out.

Such an interpretation, however, implies a very smooth radial change in the luminosity of the ionizing star clusters to generate the smoothness of the spectral gradient. Until such spatial changes in the cluster luminosity function are observed, we remain highly skeptical of this explanation and continue to favor a scenario in which the DIG is powered mainly by the major star-forming regions in these irregular galaxies. The photons ionizing the DIG are most likely leaking out of the giant H II regions and are traveling very large distances before being absorbed. Additional support for this leakage is provided by Leitherer et al. (1996) who resolved the central starburst in NGC 4214 and demonstrated that the H II region around it is density bounded.

### 3.3. Speculation on the Variations among Galaxies

Since the He ionization fraction in the DIG of these irregular galaxies is so much higher than in the Milky Way, one might question whether the extra–H II region Hz emission in Magellanic irregular galaxies is a good analogy to the Reynolds Layer in the Milky Way? Many properties of the widespread ionized gas in these galaxies are compared to those in the Milky Way DIG in Table 2. The differences are not limited to the He ionization fraction. The surface brightness of the regions studied spectroscopically in the irregular galaxies is about 5 times brighter than even the DIG in the Galactic plane studied by Reynolds. In addition to diffuse (i.e., unresolved?) emission, the DIG in the irregular galaxies contains a highly structured component of shells, arcs, and radial filaments, sometimes referred to as “interstellar froth” (Hunter & Gallagher 1990). Despite these differences, we believe the analogy is interesting because the DIG in irregular galaxies seems to share the morphology problem with the Reynolds Layer.

The He $\lambda 5876$/Hz spectral differences among different types of galaxies demonstrate that the physical conditions within the warm-ionized phase of the ISM vary. The surprisingly low He $\lambda 5876$/Hz ratio is not limited to the Milky Way. Rand (1996a) recently reported He $\lambda 5876$/Hz $\approx 0.034$ about 1.5 kpc above the plane of NGC 891, an edge-on Sbc galaxy with a prominent DIG component. The inferred He ionization, about 70%, is intermediate to irregular galaxies and the Milky Way. The high [N II] $\lambda 6583$/Hz in NGC 891 relative to the Milky Way, however, still seems to require a harder spectrum than the He $\lambda 5876$/Hz ratio (Rand 1996a).

It remains unclear why the He ionization fraction in the DIG of NGC 891 and the Milky Way is lower than expected. Compared to the irregular galaxies, the dust content and metallicity are higher, but the ionizing luminosity of the largest star-forming complexes tends to be smaller than in the irregular galaxies. Accounting for this absorption will, however, harden the Lyman continuum, thereby magnifying the discrepancy (Sokolowski 1994; Shields & Kennicutt 1995). For the Milky Way, Dove & Shull (1994) have demonstrated how the hierarchical network of Strömgren spheres created by the distributions of hot stars and gas increases the probability of an ionizing photon reaching the DIG. It is unclear whether a higher escape probability from the vantage point of large clusters in irregulars could make the escaping Lyman continuum relatively harder. We are reluctant to suggest systematic differences in the IMF since Massey (1997 and references therein) measures similar IMFs in the Magellanic Clouds and Milky Way; however, as more data become available, the possibility of systematic variations in the IMF may need to be reconsidered.

A final, but important, consideration for reconciling the interstellar Lyman continua is the accuracy of the stellar atmosphere calculations. One of the two massive stars observed with EUVE, $\epsilon$ CMa, is a case in point. The Lyman and He I continua of this B2 II star are $\geq 30$ times higher than expected, which makes it the dominant source of ionizing photons within a few hundred parsecs of the Sun (Cassinelli et al. 1995). More reliable predictions of the ionizing flux from stars this cool are needed to determine whether B stars can ionize much of the Galactic DIG. New model atmospheres for O stars including the velocity gradient in the stellar wind predict an increase in the He I continuum by several orders of magnitude (Schaerer & de Koter 1996), and similar effects are expected in the He I and Lyman continua of B stars (Najarro et al. 1996). Since the objection to ionizing the DIG in the Milky Way with late-O and early-B stars is the high total star formation rate implied (Heiles et al. 1996), we explored the effect of the new model atmospheres of Schaerer & de Koter (1996) on the required star formation rate. For the same cutoff in upper mass as that used by Heiles et al. (1996), the new model atmospheres predict a lower star formation rate because the luminosity of hydrogen ionizing photons from stars with initial masses between 16 $M_{\odot}$ and 45 $M_{\odot}$ is increased. However, the ionizing continua are also harder, and the mass of the most massive star that can contribute to the ionization of the DIG is reduced from 39 $M_{\odot}$ to 25 $M_{\odot}$ (see Fig. 3). With this revised upper mass limit on the ionizing population of stars, the implied galactic star formation rate is twice that derived by Heiles et al. (1996), which makes the discrepancy with the measured star formation rate in the Galaxy (see, e.g., McKee 1989) even larger.

### 3.4. A Consistent Picture in Irregular Galaxies

We measure a mean He $\lambda 5876$/Hz $\approx 0.040, 0.042$, and 0.043 across NGC 1569, NGC 4214, and NGC 4449, respectively, and find no evidence for a systematic variation in He $\lambda 5876$/Hz with either Hz surface brightness or distance from the nearest giant H II region. This high relative ionization fraction requires an ionizing continuum at least as hard as that supplied by a 30 $M_{\odot}$ star, which is completely consistent with the expected hardness of the radiation from the young starburst regions in these galaxies. Although the
transport of these photons over a kiloparsec to the DIG is not well understood, it seems plausible that the plethora of expanding supershells of gas in these irregular galaxies (Hunter & Gallagher 1990, 1996; Martin 1996) creates a rather porous ISM, which allows a fraction of the ionizing photons to travel large distances before absorption.

We thank Joe Shields for sharing his insight on He line emission and photoionization codes, Rich Rand and Carl Heiles for discussions about the ionization of the DIG, and Rene Walterbos, the referee, for his insightful comments. We also extend our gratitude to Craig Foltz, Mike Lesser, and Gary Schmidt for their contributions to the spectrograph and to the MMT telescope operators, Carol Heller, John McAfee, and Janet Miller, for their assistance.

Funding for this work was provided by the National Science Foundation through grant AST 94-21145. Additional support was provided by NASA through Hubble Fellowship grant HF-01083.01-96A.

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