DIFFUSE IONIZED GAS IN SPIRAL GALAXIES: PROBING LYMAN CONTINUUM PHOTON LEAKAGE FROM HII REGIONS?

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ABSTRACT

As part of a large study to map the distribution of star formation across galactic disks, we have obtained deep H\textalpha images of the nearby Sculptor Group spirals NGC 247 and NGC 7793. These images are of sufficiently high quality that they allow identification and analysis of diffuse H\textalpha emission at surface brightness levels ranging from those of extremely low density HII regions to those of the local Galactic disk diffuse emission. This paper presents a study of the large scale distribution and global energetics of diffuse ionized gas (DIG) in these galaxies and investigates the association between DIG and discrete HII regions. Our results support the hypothesis that the DIG is photoionized by Lyc photons which leak out of traditional HII regions, and suggest that the local HI column density plays a role in regulating the amount of leakage which can occur. This interpretation has profound implications for the derivation of star-formation rates based on H\textalpha emission–line fluxes since HII region counts alone will lead to significant underestimates of the true rate. The contribution of the diffuse H\textalpha component to the total H\textalpha emission, i.e. the diffuse fraction, in these galaxies is found to be similar to values found in other disk galaxies with differing Hubble types and star formation rates. The constancy of the diffuse fraction is rather unexpected and implies that the overall fraction of photons which can leak out of HII regions and ionize the ISM over large scales is relatively invariant from one galaxy to another.

Subject headings: Normal Galaxies; HII Regions; Interstellar Matter; Star Formation

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1. Introduction

Understanding the relationship between the star formation process and the interstellar medium is a key step towards unravelling the complex history of galaxy evolution. A longstanding problem has been the nature and importance of the feedback process by which massive stars deposit energy into the interstellar medium via photoionization, stellar winds and supernovae. This feedback mechanism affects the physical and dynamical state of the interstellar medium and hence influences the rate and distribution of subsequent star formation. OB stars clearly provide the largest source of Lyman continuum (Lyc) photons in typical spiral galaxies (Abbott 1982); a major issue concerns whether the bulk of these photons are deposited over localized regions, such as the Strömgren spheres which define traditional HII regions, or whether a significant fraction can escape from the regions of recent star formation where they were created and can ionize the interstellar medium over much larger scales. If large–scale ionization due to Lyc photon leakage from HII regions were a common feature of spiral galaxies, then the resulting diffuse ionized gas (DIG) component would provide an important tracer of the feedback process due to star formation, as well the structure of the interstellar medium. It would be of crucial importance to include this component in calculations of radial and global star formation rates derived on the basis of Hα emission line fluxes. Furthermore, the existence of such a DIG component would have direct bearing on the energy balance of the interstellar medium, regardless of the source of photons that maintain it in an ionized state.

Indeed, the existence of widespread diffuse ionized gas lying outside the boundaries of traditional HII regions has been known for over 20 years (Reynolds et al. 1971; Monnet 1971), but the source of this ionization remains the subject of much debate. Pulsar dispersion measures and optical line emission have been used to trace the Galactic DIG component (the ‘Reynolds Layer’) and have established it to be an extremely important component of the interstellar medium, occupying more than 20% of the interstellar volume, contributing at least \( \frac{1}{3} \) of the total HI column at the solar circle and constituting \( \sim 90\% \) of the ionized hydrogen mass in the Galaxy (see review by Reynolds 1991 and references therein). The location of the Sun close to the plane of the disk of the Milky Way means that the vertical structure of the ionized gas is more easily studied than is its radial distribution; it has been established that the Galactic DIG is distributed in a thick disk with a scale–height locally of \( \sim 1 \text{ kpc} \). Much of the DIG (sometimes referred to as the Warm Ionized Medium; WIM) is observed to be in the form of discrete structures, such as loops, filaments and shells (which are not obviously associated with discrete HII regions) while the remainder is in the form of an apparently unstructured, diffuse background (Reynolds 1993). The power required to maintain this low-density (\( n_e \sim 0.1 \text{ cm}^{-3} \)), warm (\( < 10000 \text{ K} \)) ionized component is large – \( 1.0 \times 10^{-4} \text{ erg s}^{-1} \text{ cm}^{-2} \) of disk – and can be met easily only by ionizing photons from OB stars, although the kinetic energy from supernovae could possibly suffice (Reynolds 1984; Kulkarni and Heiles 1988).

The identification of OB stars as the source of the ionization of the Galactic DIG would require
that Lyman continuum photons be able to travel several hundred parsecs both perpendicular
to the plane, to account for the derived vertical scale–height of a kiloparsec, and parallel to the
plane, to account for the DIG seen at large radial distances from OB stars (see Reynolds 1990).
These requirements are even greater in irregular galaxies, where ionized gas has been observed
at distances of $\gtrsim 1$ kpc from bright OB associations (Hunter and Gallager 1990; Hunter and
Gallagher 1992). Recent calculations suggest that it is indeed possible for a large fraction of
ionizing photons to penetrate sufficiently large distances from their point of origin, depending on
cloud properties and distributions, as well as on their radial gas distributions (Dove and Shull
1994; Miller and Cox 1993). The observed optical emission line ratios of the Galactic DIG can
be explained by a rather dilute radiation field and hence argue further for photoionization by
distant OB stars (Dömgorgen and Mathis 1994). Alternative sources for the ionizing radiation
that maintains the DIG which have been proposed include shocks, decaying massive neutrinos
(Sciama 1990), turbulent mixing layers (Slavin, Shull and Begelman 1993) and Galactic microflares
(Raymond 1992). In addition, significant contributions to the ionizing flux may come from evolved
stellar objects such as planetary nebula nuclei, hot white dwarfs and blue horizontal branch stars.

The large scale radial distribution of the DIG across galactic disks can provide stringent
constraints on the source of its ionization. For example, if the amount of Lyc photons produced
in star–forming regions were the only factor responsible, then the DIG distribution and intensity
should be expected to correlate, over both small and large scales, with that of discrete HII
regions. Furthermore, DIG properties should also be expected to vary systematically with the
morphological type of the host galaxy, reflecting the underlying variation in star formation and
structure within the ISM (Kennicutt, Edgar and Hodge 1989). Study of such correlations requires
observations of external galaxies at moderate inclinations. To date, few quantitative studies of the
DIG in external galaxies have been carried out, and the emphasis has largely been on edge–on
systems (eg. Rand, Kulkarni and Hester 1990; Dettmar 1992; Veilleux et al. 1995). Walterbos and
Braun (1994; hereafter WB94) studied the DIG component in selected areas of the nearby spiral
M31, but their small field of view restricted them to local analysis and they could not assess the
overall distribution and energetics of the ionized gas they detected.

The first quantitative study of the large–scale distribution and global energetics of diffuse
ionized gas in moderately face–on external disk galaxies is presented in this paper. Our data
consist of large field of view, deep Hα images of Sculptor Group late–type spirals NGC 247 and
NGC 7793 which were obtained as part of a large study to map the distribution of star formation
across galactic disks. NGC 7793 has been previously noted for having a significant DIG component
(Monnet 1971) but this earlier work was limited to photographic data, with surface brightness and
spatial resolution limits significantly lower than the CCD data presented here. Basic properties
of these galaxies are listed in Table 1. In the present paper, we derive the radial and azimuthal
distributions of the DIG and investigate the association between DIG and discrete HII regions. We
also study the global and radial variation of the diffuse fraction and the Lyc power requirements,
which allow tight constraints to be placed on the origin and nature of DIG component in spiral
Our results support the hypothesis that the DIG is photoionized by Lyc photons which leak out of discrete HII regions, and suggest that the local HI column density plays a role in regulating the amount of leakage which can occur. Given this hypothesis, we discuss the great importance of taking account of the DIG component when deriving star formation rates based on Hα emission line fluxes.

2. Observations and Data Analysis

The observations were carried out at the Cerro Tololo Inter-American Observatory (CTIO) during the nights of December 14 – 18, 1993 and September 28 – October 2, 1994. Images were obtained with the Tek 2048 × 2048 CCD on the 1.5m telescope, at f/7.5. The resulting pixel scale was 0.44″ and the field of view was 15' on a side, corresponding to physical sizes of approximately 6 pc and 13 kpc, respectively, at the mean distance of our galaxies. The Hα filter was 68 Å wide (FWHM) centered on 6554 Å and encompassed the [NII] lines. A broadband R filter was used for the continuum observations. Total exposure times ranged from 3600 – 5700 secs in Hα and from 600 – 840 secs in R. The seeing was in the range of 1.2 – 2.5″.

The large angular extent of the galaxies on the sky – 25th magnitude isophotes of 10.1’ × 6.1’ for NGC 7793 and 5.4’ × 19.9’ for NGC 247 (Carignan 1985) – resulted in several fields being required to map each galaxy completely. Using the ‘shift and stare’ technique, we imaged each galaxy in two sections along the major axis. Well–exposed, median–filtered twilight sky frames were used to flat-field the images, and all frames were corrected to an airmass of zero. Images of each section were registered and those taken through the same filter were combined using an average sigma-clipping algorithm. The sky to be subtracted was determined in each of these combined Hα and R–band frames as the mean of the mean pixel value in a series of 100 × 100 pixel boxes positioned well outside the Holmberg diameters. The uncertainty in the determination of the sky value due to large scale flat–fielding errors was less than or equal to 1% in each case. Foreground stars in the frames were used to determine the scaling factors between the Hα and R–band images, and the scaled continuum images were subtracted from the Hα.

Observations of standard stars from the list of Stone and Baldwin (1983) were used to calibrate the Hα images. Instrumental magnitudes of several stars were measured on the Hα continuum–unsubtracted images. Standard magnitudes were derived from Stone and Baldwin (1983) by integrating the interpolated flux at Hα across the filter band–pass, assuming a top–hat transmission curve. Comparison of the two magnitudes provided the conversion between observed counts and absolute flux. There are no previously measured HII regions with which to compare our measurements. Our neglect of factors such as the true shape of the filter transmission curve and the variation of stellar flux across the band–pass is likely to lead to uncertainties in the calibration factor of ± 20%. The average sensitivity of the Hα continuum-subtracted images,
taken to be 1σ of the sky background, is $4.3 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ pix}^{-1}$ for the NGC 7793 image, and $6.4 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ pix}^{-1}$ for the NGC 247 image. These values correspond to emission measures (EM) per pixel of $\sim 11 \text{ pc cm}^{-6}$ and $\sim 16 \text{ pc cm}^{-6}$ respectively, for an assumed electron temperature of $10^4 \text{ K}$. The scaled R–band images had sufficiently high S/N that the noise in the Hα continuum–subtracted images was limited by the noise in the original Hα frame alone.

The two separate Hα continuum–subtracted images of each galaxy were mosaiced together to give a field of $13.8' \times 17.5'$ centered on NGC 7793 and $10.6' \times 23.8'$ centered on NGC 247. In the mosaicing process, care was taken to ensure that fluxes of objects common to both frames were matched. The sky levels across the mosaiced images were measured in areas beyond the Holmberg diameters and were $0 \pm 1.5 \text{ pc cm}^{-6}$ in the NGC 7793 frame and $0 \pm 3.2 \text{ pc cm}^{-6}$ in the NGC 247 frame. This combination of low sky noise, small flat–fielding errors and a large number of pixels allows us to reach very low Hα+[NII] surface brightnesses, comparable to those observed locally in the Reynolds layer ($\sim 6 \text{ pc cm}^{-6}$; Reynolds 1984). Thus, a direct comparison of the diffuse ionized ISM in the Milky Way and in external galaxies can be made.

A bright, foreground star was present in the field of NGC 247. Pixels contaminated by emission from this star were masked out and subsequently ignored in the analysis. Hα continuum–subtracted, mosaiced images of NGC 7793 and NGC 247 are shown in Figure 1 at two different surface brightness cuts.

3. Isolating the Diffuse Hα Emission

The separation of total Hα flux into that from discrete HII regions and that from diffuse emission is somewhat complex and subtle and there is as yet no standard procedure. Various criteria have previously been adopted, for example based on the strength of forbidden line ratios (WB94) or on the equivalent width of the Hα line (Veilleux et al. 1995). The current limited information available concerning how DIG properties and excitation vary within and between galaxies prevents a rigorous assessment of how appropriate either of these methods is for isolating the diffuse emission in a truly unbiased manner. A much simpler approach to the separation, based on surface brightness, is adopted here. We experimented with our images until we found a simple isophotal cut which eliminated the bulk of the discrete HII region population. This cut was made at a surface brightness of $1.6 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \square''$, uncorrected for [NII] or extinction, corresponding to an EM of $80 \text{ pc cm}^{-6}$ per pixel (for an assumed T_e = $10^4 \text{ K}$); most of the Hα emission lying below this could be classified as filamentary and/or diffuse. For comparison, this isophotal cut is lower than the limits employed by recent studies of discrete HII region populations.

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1. Emission measure is related to Rayleighs, the commonly used unit of surface brightness in Galactic DIG studies, by $\text{EM (pc cm}^{-6}) = 2.78 \times I_{Hα} \text{ (Rayleighs)}$ for $T_e=10^4 \text{ K}$. 

in spiral galaxies (Scowen 1992; Kennicutt et al. 1988) and also lower than the isophotal limit which WB94 found isolated the bulk of the diffuse Hα emission in M31 (EM < 100 pc cm$^{-6}$). Hence, the present approach to the separation of the two components of the Hα emission is a conservative one. Figure 2 illustrates the diffuse Hα emission in high–resolution subsections of each galaxy, by masking out pixels having EM > 80 pc cm$^{-6}$.

The moderate inclinations of the galaxies studied here do not allow us to determine whether diffuse Hα emission is also superimposed on discrete HII regions, though this is very likely to be the case. We point out that the observed DIG properties are derived only from pixels uncontaminated by the emission of HII regions, and hence are strictly lower bounds to the true values.

It is of great importance to verify that the diffuse Hα emission we detect is indeed a distinct source of emission (ie. ionized locally) and not simply recombination photons which are scattered out of discrete HII regions. Following WB94, we consider two possible distinct mechanisms for light scattering that could occur.

First, light could be scattered in the telescope and detector system, producing extended wings to the point spread function and possibly containing a significant fraction of the total light. To check for such an effect, we carried out aperture photometry of several bright stars in the Hα frames of both galaxies. The stars chosen were isolated and far removed from any galaxian light. In every case, at least 95% of the total emitted light was enclosed within an aperture of radius 11 pixels, corresponding to 4.8″. The results of the aperture photometry were used to derive azimuthally–averaged radial surface brightness profiles, which revealed that the total decline in surface brightness ($\sim 10$ mag/″) occurred over a radius of only 15 – 20″. Beyond this radius, much less than one percent of the total Hα light remained. As a result, if the diffuse emission were merely Hα light from HII regions, scattered by the telescope optics, then it should be highly localised around those regions and the luminosity of the diffuse component should be significantly less than that of the discrete HII regions. As we will discuss below, there is no evidence for either of these requirements. Furthermore, the distinct structure of the brighter diffuse emission – filaments, bubbles, loops – cannot be explained if the diffuse emission were simply the result of scattered Hα photons in the telescope and detector system.

The second type of scattering which could occur is reflection from dust grains in the HII regions themselves. Since there is no evidence for halos around bright OB associations in the R–band continuum images, which should suffer equally, if not more, from the effects of dust scattering than the Hα images, we conclude that the role of this second type of scattering is also negligible. We will henceforth refer to the diffuse Hα emission we have detected as diffuse ionized gas (DIG).

4. Results
4.1. The Morphology of The Diffuse Ionized Gas

The observed morphology of the DIG, and its variation within and between galaxies, provides important clues to its origin. Our deep Hα images reveal a wealth of structure in the ionized gas components of the galaxies studied here.

The HII regions in NGC 247 are small, faint and widely separated. The brightest HII regions have Hα luminosities of $\sim 5 \times 10^{38}$ erg/s, which is slightly lower than the luminosities of the brightest Galactic HII regions, and considerably lower than the luminosities of the brightest HII regions found in late–type galaxies such as the LMC and M101 (Kennicutt 1984). Much of the DIG in NGC 247 is localized around individual star–forming regions, enveloping them in frothy, filamentary halos. The HII regions and the DIG are largely concentrated into two spiral arms. In the inner regions of the disk and in the spiral arms, the DIG halos merge together at faint intensity levels. We do not detect any DIG emission from the interarm regions.

The disk of NGC 7793 is characterized by many luminous HII regions/complexes (typical luminosities $\gtrsim 10^{39}$ erg/s) and bright DIG uniformly fills the spaces in between them, out to more than half of the optical radius of the galaxy. This high covering factor of DIG means that it is difficult to associate a given patch of DIG emission with any particular star–forming region in the inner regions of the disk. Further out, the bright DIG tends to be more associated with individual HII complexes, but all outer disk structures merge together at faint levels of a few pc cm$^{-6}$. NGC 7793 lacks well–defined spiral structure and is instead characterized by a chaotic pattern of arm fragments. This is reflected in both the distribution of HII regions and the distribution of the DIG.

The HII regions in NGC 7793 fill a higher fraction of the disk area than do those in NGC 247. As discussed below in Section 5.3, NGC 7793 has a global star formation rate roughly three times higher than that inferred for NGC 247. Furthermore, this star formation is occurring over a physical area which is less than half the size of that over which star formation is occurring in NGC 247. Qualitatively, it appears that the DIG intensity and covering factor is strongly tied to the star formation rate per unit area in these galaxies.

In addition to the relatively unstructured DIG, both galaxies show some evidence for bubbles, loops and filamentary features, extending up to a few hundred parsecs in size. Such features are considered clear evidence for the action of massive stars on the environment (Tenorio–Tagle and Bodenheimer 1988). Some of these features have sufficiently high surface brightnesses that they lie above our surface brightness limit for the DIG and hence their emission is classified as being due to discrete HII regions. The features we observe in NGC 7793 and NGC 247 are much less spectacular than features we have identified in two other Sculptor disk galaxies, NGC 55 and NGC 300 (Ferguson et al., in preparation). They are also smaller in size than the supergiant shells which have been identified in the LMC, a galaxy which is of similar absolute magnitude and present star formation rate to the ones studied here, but lacking in spiral arms (however several of
these supergiant shells have surface brightnesses which lie above our criterion for diffuse emission (Hunter 1994)). It is tempting to speculate that the sizes of the filamentary and bubble-like features, which constitute the structured component of the DIG, are a direct result of the intensity of local star formation, however magnetic fields may play an equally important role in regulating their morphologies (Elmegreen 1987; Hunter and Gallagher 1990).

### 4.2. The Distribution of Diffuse Ionized Gas

#### 4.2.1. Azimuthal Variation

The azimuthal variation of Hα emission provides important information on the uniformity of the intensity distribution of the DIG and on the spatial association between bright HII regions and the DIG. Figure 3 shows the azimuthal variation of Hα+[NII] emission measure around a series of four elliptical annuli, chosen to span a large fraction of the optical disk in each galaxy. The emission measures have not been corrected for extinction. The radial thickness of each annulus is 250 pc and the data are binned in 2° sectors around the azimuthal direction. The adoption of a fixed angle for azimuthal binning results in a variable smoothing factor in terms of pixels. For example, in NGC 7793, the azimuthal bin size corresponds to physical areas of size $\sim 250 \text{ pc} \times 15 \text{ pc}$ and $\times 135 \text{ pc}$ in the annuli centered on 0.1R$_{25}$ and 0.9R$_{25}$ respectively. In NGC 247, the bin sizes are $\sim 250 \text{ pc} \times 19 \text{ pc}$ and $\times 175 \text{ pc}$ in the 0.1R$_{25}$ and 0.9R$_{25}$ annuli. For reference, small Galactic HII regions have typical diameters of a few tens of parsecs and hence would be smoothed over in our analysis. While this may account for some of the low surface brightness emission seen in the azimuthal profiles in Figure 3, visual inspection of the images reassures us that the bulk of this emission arises from truly diffuse and filamentary structures. The largest HII region complexes found in late-type spirals have diameters of order a few hundred parsecs (Kennicutt 1984) and hence would be preserved in our azimuthal plots, if centered.

Two key results emerge from the azimuthal analysis. Firstly, in the inner radial bins of both galaxies, the DIG fills the annuli uniformly defining a *baseline* in the value of the emission measure. This baseline is $\sim 100 \text{ pc cm}^{-6}$ in NGC 7993 and $\sim 20 \text{ pc cm}^{-6}$ in NGC 247. As the radial distance from the center of each galaxy increases, this baseline value gradually decreases and in the outermost bins here, the Hα emission often becomes too faint to detect far from bright HII regions and complexes. Secondly, our azimuthal plots reveal that bright HII regions/complexes often have substantial halos which blend smoothly into the DIG. The brightest DIG emission appears to be closely associated with sites of recent star formation and the intensity of the DIG is observed to fall off with distance from the nearest HII region. The plots confirm that, in the inner disks of both galaxies, it is impossible to associate a given patch of DIG emission with any particular HII region. At larger galactocentric distances, however, much of the DIG is localized around bright OB complexes, although these are few in number.
Fig. 3.— (a) Plot of the azimuthal variation of uncorrected Hα +[NII] surface brightness at four radii in NGC 7793. The radii correspond to 0.1R\textsubscript{25}, 0.3R\textsubscript{25}, 0.6R\textsubscript{25} and 0.9R\textsubscript{25}. The width of each radial bin is 250 pc and the data are azimuthally binned into 2° sectors. (b) As in (a) but for NGC 247.

The radial and azimuthal smoothing above, while facilitating qualitative analysis, hampers the derivation of quantitative information on the typical scales on which DIG is associated with individual HII regions. Direct inspection of the images (Figures 1 and 2) reveals that DIG can be found up to distances in the range of 200 – 900 pc from bright HII regions, with a typical extent of around 500 pc. Clearly, the brighter DIG is associated with HII regions, but at fainter levels, it becomes ubiquitous.

4.2.2. Radial Variation

In order to study the radial variation of the ionized gas components in these galaxies, we carried out elliptical aperture photometry on our H\alpha images, using ellipses fit to the corresponding R–band images. This approach was chosen since the H\alpha images themselves are too clumpy for meaningful ellipses to be fit. The radial step size was 350 pc for NGC 7793 and 500 pc for NGC 247. Radial surface brightness profiles were derived for the total H\alpha emission, the H\alpha emission from HII regions alone, and the H\alpha emission from the DIG (using the isophotal
surface brightness criterion discussed previously). In calculating the DIG surface brightness, we normalised to the number of pixels that had a surface brightness less than $80 \text{ pc cm}^{-6}$, as opposed to the total number of pixels per annulus. This approach freed us from making assumptions about the intensity of the DIG that is superimposed on bright HII regions. A deprojection was carried out ($\cos(i)$ correction) using the values of the inclination listed in Table 1. We note that if the DIG emission arises in a thick–disk component then the thin-disk correction we have applied will result in an underestimate of the true radial surface brightness amplitude. In this case, the deprojection becomes a complicated function of the radial and vertical profiles of the ionized gas disk and the dust.

The discrete and diffuse Hα emission was corrected separately for contamination by the [NII] lines and for the effects of Galactic and internal extinction. Webster and Smith (1983) have presented spectra for various HII regions in the disk of NGC 7793. We have used these data to derive the disk-averaged $I([\text{NII}])/I(\text{H}\alpha)$ ratio and the Balmer decrement, $C_{\text{H}\beta}$, for the HII regions in NGC 7793 with the result that $[\text{NII}]/\text{H}\alpha_{\text{HII}} = 0.22$ and $C_{\text{H}\beta}=0.38$. We note that the data available indicate no significant change in the $[\text{NII}]/\text{H}\alpha$ ratio across the disk (even although the galaxy has a moderately steep metallicity gradient). The reddening law of Schild (1977) then gives an extinction of $A_{\text{H}\alpha}=0.64$. Spectroscopic information does not exist for any HII regions in NGC 247, so the $[\text{NII}]/\text{H}\alpha$ ratio and the mean extinction values derived for NGC 7793 were assumed equally applicable for NGC 247. Thus, the derived quantities for NGC 247 are more uncertain than those for NGC 7793. There has not been a direct measurement of the $[\text{NII}]/\text{H}\alpha$ ratio in the DIG component of the galaxies presented here; however, studies of other galaxies indicate that this ratio is often systematically higher than that measured for discrete HII regions (Dettmar 1992; Dettmar and Schultz 1992; Veilleux et al. 1995; Hunter 1994). We adopt $[\text{NII}]/\text{H}\alpha_{\text{DIG}}=0.50$ to be consistent with the mean values found in those studies. In the absence of data which can be used to constrain directly the extinction of the diffuse gas (eg. WB94), we adopt the same extinction correction for both the DIG and the discrete HII regions unless otherwise noted. Figure 4 shows the radial variation of the ionized components measured out to the optical radius and corrected for our adopted [NII] contamination and extinction. In both galaxies, we clearly detect DIG over a large fraction of the star-forming disks (ie. to $\sim R_{25}$).

Very different Hα profiles are observed across the two galaxies. NGC7793 has a centrally peaked Hα profile with a region of very active star formation, as traced by the HII regions, occurring out to a galactocentric radius of $\sim 3$ kpc. The total average emission measure falls off quite steeply, ranging from $\gtrsim 250 \text{ pc cm}^{-6}$ in the center of the galaxy, to a few pc cm$^{-6}$ in the outer parts of the disk. The DIG emission measure ranges from $\sim 60$ pc cm$^{-6}$ in the center, to a few pc cm$^{-6}$ in the outer galaxy. The DIG profile in NGC7793 is much flatter than that of the HII regions in the inner disk, but the profiles become very similar beyond a radius of $\sim 2.5$ kpc. Part of the central flattening must be due to the present definition of DIG; some high surface brightness ($\text{EM} \simeq 150 \text{ pc cm}^{-6}$), truly diffuse emission is clearly visible in the inner regions of the galaxy but has been misclassified by our separation technique. If properly included, the two inner
Fig. 4.— (a) Deprojected radial profile of the total Hα surface brightness (solid line), the Hα surface brightness derived by counting HII regions alone (dashed–dotted line) and the Hα surface brightness of the DIG (dashed line) in NGC 7793. The optical radius (R25) is indicated. (b) As in (a) but for NGC 247.

profiles would possibly show a more similar behaviour.

On the other hand, NGC247 is characterized by very low Hα surface brightnesses across its disk, at least a factor of 10 below those observed in NGC7793 at similar radii, and has an extremely flat profile with only a weak central enhancement. The radial distribution of the diffuse ionized component closely follows that of the HII regions throughout the entire disk. The DIG emission measure ranges from 12 pc cm$^{-6}$ in the center to a few pc cm$^{-6}$ in the outer regions, with the bulk of the disk having a DIG surface brightness of around 5 pc cm$^{-6}$. Thus, in NGC 247 we have made a detection of an extragalactic ionized hydrogen disk of comparable surface brightness to that measured locally in the Reynolds layer ($\sim 6$ pc cm$^{-6}$; Reynolds 1984).

4.3. The Diffuse Fraction

4.3.1. Global Values

The observed total luminosity of the DIG in each galaxy was obtained by summing the intensities of pixels with observed surface brightnesses corresponding to an EM $< 80$ pc cm$^{-6}$ and then correcting for contamination by [NII] and extinction as described above. The observed Hα DIG luminosities are found to be $7.5 \times 10^{39}$ erg s$^{-1}$ for NGC 247 and $1.2 \times 10^{40}$ erg s$^{-1}$ for NGC 7793. The observed global diffuse fractions, defined to be the fraction of the total Hα
luminosity contributed by the DIG, are 50% for NGC 247 and 29% for NGC 7793. Lower limits on the diffuse fraction may be derived by the assumption of zero extinction for the diffuse gas and are 37% for NGC 247 and 19% for NGC 7793.

As previously mentioned, the observed DIG Hα luminosities are strictly lower bounds to the true Hα luminosities since they are derived on the assumption that the intensity of the DIG is zero on top of discrete HII regions. A more realistic estimate of the luminosity of the DIG can be derived as follows. We assume that each elliptical annulus is filled with DIG at the mean DIG surface brightness measured at that particular radius (as indicated in the DIG surface brightness profiles presented in Figures 4a and b). In essence, this amounts to counting a fraction of the flux from each HII as being emission due to superimposed DIG. This is a small effect everywhere except in the innermost bins, where the HII region covering-factor is significant, and is still likely to give an underestimate of the true Hα luminosity of the DIG. The total DIG luminosities of all the individual annuli are then summed and corrected for [NII] and extinction. The resulting corrected DIG Hα luminosities are $7.9 \times 10^{39}$ erg s$^{-1}$ for NGC 247 and $1.7 \times 10^{40}$ erg s$^{-1}$ for NGC 7793. We note that the corrected DIG Hα luminosity in NGC 247 is only slightly larger than the observed one; this is due to the small covering factor of bright HII regions across the disk of the galaxy. These values can be used to calculate the corrected global diffuse fractions with the result of 53% for NGC 247 and 41% for NGC 7793.

The global diffuse fractions derived here are very similar to the global diffuse fractions found in other actively star-forming nearby galaxies (but being mindful of the wide range of assumptions and corrections that different authors have applied): 40% in M31 (WB94); 30% in NGC 3079 (Veilleux et al. 1995); 35% in the LMC; 41% in the SMC (Kennicutt et al. 1995) and 35% and 50% in the Magellanic Irregulars NGC 4214 and NGC 4449 (Kennicutt et al. 1989). (Note that Hunter and Gallagher (1990) find lower diffuse fractions, 15% – 20%, in NGC 4214 and NGC 4449; this may be due to the lower isophotal surface-brightness cut they used to define the DIG.) Diffuse fractions in this general range were also inferred for a large sample of nearby spirals on the basis of emission-line ratios in their integrated spectra (Lehnert & Heckman 1994). The similarity in the measured diffuse fractions is somewhat surprising given the wide range of morphological types (Sb – Im) and star formation rates (0.01 – 0.6 M$_\odot$ yr$^{-1}$) spanned by these galaxies. Furthermore, several of these galaxies have large kpc-scale ionized bubble and filamentary features (NGC 3079, LMC, SMC, NGC 4449) while others do not. Such obvious signs of HII region disruption do not appear to lead to relatively larger quantities of DIG. One possible interpretation of this result is that the overall fraction of photons which leak out from HII regions is relatively constant from galaxy to galaxy, appearing at first glance to be largely independent of star formation and ISM properties. Alternatively, it could reflect the fact that these galaxies all have a significant fraction of their OB star population residing outside the boundaries of classical HII regions (eg. Patel and Wilson 1995).
4.3.2. Radial Variation

The variation of the diffuse fraction within a given galaxy is of considerable interest since it constrains the origin of the DIG. We calculated this quantity by taking the ratio of DIG luminosity to total Hα luminosity in the series of elliptical annuli used for deriving the radial profiles. In view of the artificially low values of the diffuse fraction we derived in the inner regions, where few pixels are uncontaminated by bright HII regions, we assumed again that the DIG emission filled each ellipse at the mean surface brightness measured. Figure 5 shows the radial variation of the diffuse fraction across the disks of NGC 7793 and NGC 247. The diffuse fraction is almost constant at \( \sim 50\% \) across the disk of NGC 247, whereas it rises in NGC 7793 from \( \sim 30\% \) in the inner regions to \( \sim 90\% \) in the outermost parts. The suspected under-counting of DIG due to misclassification in the inner disks may account for part of the radial trend seen in NGC 7793 but cannot explain the entire amplitude.

![Radial variation of the diffuse fraction for NGC 7793 (left) and NGC 247 (right).](image)

Fig. 5.— Radial variation of the diffuse fraction for NGC 7793 (left) and NGC 247 (right).

Our results for the radial variation of the diffuse fraction are in qualitative agreement with the predictions of recent models for the photoionization of the DIG by Lyc photon leakage from OB associations (Dove and Shull, 1994). These models incorporate a smoothly varying HI distribution, and thus are limited in the sense that they do not allow for structure in the HI or for a population of opaque clouds. In these models, the radial profile of HI plays a role in determining the radial variation of the diffuse fraction, with the fraction of ‘escaped’ Lyc photons being essentially proportional to a constant plus \( R/R_g \), where \( R_g \) is the HI gas scale-length (their equation 30). If the HI profile is flat, i.e. \( R_g = \infty \), then the ‘escaped’ fraction is predicted to be constant across a disk. Both galaxies discussed here have declining HI profiles over their optical disks. The decline in NGC 7793 is much steeper (i.e. shorter scale-length) and takes place over a larger fraction of
the disk than that observed in NGC 247 (Carignan & Puche 1991; Puche & Carignan 1991). As a result, the Dove and Shull (1994) models predict that the diffuse fraction should rise more steeply in NGC 7793 than in NGC 247, consistent with the observations.

4.3.3. Errors

It is important to quantify the effects that small errors in the flat-fielding, sky subtraction and/or the continuum subtraction could have on the derived luminosities and hence the global diffuse fractions presented above.

As discussed previously, the sky value is determined for each combined Hα and continuum frame, and subtracted off before the continuum subtraction and mosaicing is carried out. Any small error in the sky determination for a given frame could become more significant in the final Hα continuum–subtracted mosaiced image. As discussed in Section 2, we determined the sky level across the final mosaiced images using small (100 × 100 pixels) boxes situated beyond the Holmberg diameters of each galaxy. The sky values obtained were 0 ± 1.5 pc cm\(^{-6}\) in the NGC 7793 frame and 0 ± 3.2 pc cm\(^{-6}\) in the NGC 247 frame. Assuming a maximum error in the sky of ±1.5 pc cm\(^{-6}\) across the entire field of NGC 7793, the resulting error in the corrected DIG Hα luminosity would be ∼ 6%, the error in the total Hα luminosity would be ∼ 2% and the error in the corrected global diffuse fraction would be ∼ 2%. Likewise, an assumed maximum error of ±3.2 pc cm\(^{-6}\) across the entire field of NGC 247 leads to an error in corrected DIG Hα luminosity of ∼ 32%, an error in total Hα luminosity of ∼ 17% and an error in the corrected global diffuse fraction of ∼ 8%. The larger errors for derived quantities in NGC 247 result from a combination of a larger sky error per pixel and a larger number of pixels covered by the galaxy. While these simple calculations neglect the fact that adjusting the sky value also affects our classification of emission as being either diffuse or discrete, they serve to give a rough idea of the stability of our derived quantities to realistic errors in the sky background.

Another source of possible uncertainty lies in the continuum scaling factor used to produce the final Hα continuum–subtracted images. As previously discussed, the continuum scaling factor was derived by measuring the ratio of the fluxes of foreground stars in the Hα and continuum images. The scale factor was slightly adjusted until the bulk of the foreground stars were perfectly subtracted and there were no large positive or negative regions across the galaxy, as judged by eye. We experimented with changing the scaling factor by ±2% and then by 7%, and noted how this affected our derived quantities. For both galaxies, a 2% change in the scaling factor led to changes of ∼ 5–8% in the corrected DIG Hα luminosities, ∼ 5% in the total Hα luminosities and no appreciable change in the corrected global diffuse fractions. Changing the continuum scaling factor by 7% led to changes of ∼ 25% in the corrected DIG Hα luminosities, ∼ 15% in the total Hα luminosities and ∼ 5% in the corrected global diffuse fractions. We note that a 7% change in
the continuum scaling factor corresponds to the point at which spurious large scale positive and negative variations become clearly visible across the galaxies and foreground stars are improperly subtracted; thus, this is the maximum possible error on the derived continuum scaling factor.

Application of a single continuum scaling factor across the disk of the galaxy, as done here, implicitly assumes no gradient in the \( \text{H} \alpha \) equivalent width. This may not be entirely appropriate but is expected to be a low amplitude effect.

4.4. Lyc Power Requirements

The deprojected, \([\text{NII}]\)– and extinction-corrected radial profiles of the DIG in these galaxies can be used to calculate the minimum power per unit area required to keep the DIG ionized. The recombination rate per cm\(^2\) of disk, \( r \), is first calculated using the relation

\[
r = \frac{4 \pi}{\epsilon} I_{\text{H}\alpha},
\]

where \( \epsilon \) is the average number of \text{H} \( \alpha \) photons per recombination (assumed to be \( \sim 0.46 \); Case B recombination at \( 10^4 \) K) and \( I_{\text{H}\alpha} \) is the \text{H} \( \alpha \) surface brightness in units of photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\); the power consumption per unit area is then derived under the assumption that every ionization requires a minimum input energy of 13.6 eV. These power requirements are plotted in Figure 6, where the dashed line indicates the value estimated for the solar neighborhood, \( 1 \times 10^{-4} \) erg s\(^{-1}\) cm\(^{-2}\) (Reynolds 1984). As can be seen, NGC 7793 has minimum power per unit area requirements which are significantly higher than the local Galactic value, whereas NGC 247 has requirements which are similar to the Milky Way.

Based on the observed total DIG \text{H} \( \alpha \) luminosities discussed in Section 4.3.1, we can derive the minimum integrated Lyman continuum power required to keep the DIG ionized, using the same procedure as outlined above. We find minimum Lyc power requirements of \( 1.2 \times 10^{41} \) erg s\(^{-1}\) for NGC 247 and \( 1.9 \times 10^{41} \) erg s\(^{-1}\) for NGC 7793. If we use the more realistic corrected \text{H} \( \alpha \) luminosities of the DIG, we derive power requirements of \( 1.25 \times 10^{41} \) erg s\(^{-1}\) for NGC 247 and \( 2.7 \times 10^{41} \) erg s\(^{-1}\) for NGC 7793. These values are all slightly lower than the Galactic one of \( 6 \times 10^{41} \) erg s\(^{-1}\) (Reynolds 1984), which was derived on the basis of extrapolating local values over the entire disk. The galaxies studied here are smaller than the Milky Way and hence lower global power requirements are not unexpected. Nevertheless, the enormous amount of power required to sustain the DIG in these galaxies (at least \( 3 - 5 \times 10^7 \) L\( \odot \) in Lyc photons alone) places severe constraints on the possible origin of the ionizing photons.

5. Discussion
Fig. 6.— Minimum power per unit area required to maintain the DIG across the disk of each galaxy. The dotted line indicates the value derived for the solar neighborhood (Reynolds 1984).

5.1. Small and Large Scale Distribution of the DIG

The azimuthal and radial intensity distributions of Hα emission in these galaxies indicate that the DIG is highly correlated with bright HII regions over a variety of scales. On scales of a few hundred parsecs, the bright DIG is highly concentrated around luminous HII regions, with the mean surface brightness decreasing as the distance to the nearest HII region increases. This close small-scale association between DIG and HII regions was also observed by WB94 in selected fields in M31 and lends strong support for a model in which the Lyc photons which ionize the DIG leak out of individual HII regions. In this picture, the bulk of the Hα recombinations would be expected to take place in the immediate vicinity of the leaking HII region, where the Lyc photon flux is higher. At faint levels, the DIG is ubiquitous, though generally follows the overall pattern of star formation e.g. being enhanced in spiral arm structures if present, as in NGC 247.

Over larger scales, the DIG has spatial and intensity distributions which closely follow those of the discrete HII regions in each galaxy. A key observation is that the DIG is detected over the entire extent of the bright star–forming disks in both galaxies. The faint, outer disk DIG we detect has surface brightnesses comparable to the large–scale flat–fielding errors, hence we are unable to address the important issue of whether the region of DIG emission actually extends beyond the edge of the HII region distribution. Deeper CCD data we have just obtained for these galaxies will allow a more detailed future study of the outer disk DIG emission.
The large scale radial distributions reveal that the DIG intensity falls off with the mean surface brightness of HII regions and, hence, the mean level of star formation. Hester and Kulkarni (1990) and Veilleux et al. (1995) have also noted a large scale radial variation of DIG intensity, in studies of M33 and NGC 3079 respectively, but they did not make a comparison with the distribution of discrete HII regions in these galaxies. The similarity between the DIG and the discrete HII region surface brightness profiles observed further supports a leakage origin for the ionizing photons which create the DIG. Moreover, the correlation between the mean surface brightness of discrete HII regions and the DIG suggests that large–scale radial photon transport, on scales comparable to the widths of our annular bins, 250 pc, does not involve a significant number of ionizing photons.

The small and large scale distributions of the DIG are easily understood in terms of a model where Lyc photon leakage from star–forming regions provides the dominant source of the ionizing photons. The available evidence indicates that the star formation rate per unit area (traced by the surface brightness of discrete HII regions) is correlated with the DIG surface brightness, in the sense that a higher mean star formation rate per unit area leads to a higher number of Hα recombinations occurring outside of discrete HII regions. The leakage model is not the only model which can explain our observations of the large scale distribution of the DIG, however, and any method of producing ionizing photons which is tied to Population I objects is equally plausible. A model in which a significant fraction of the OB star population resides outside the boundaries of discrete HII regions may also suffice (eg. Patel and Wilson 1995), but it remains unclear whether ionization by in situ OB stars can explain other DIG properties, such as the observed line ratios. Decaying neutrinos might be expected to produce an ionized gas component with a radial profile similar to the density profile of the dark matter halo, ie. volume density proportional to the inverse square of the radius (Sciama & Salucci 1990). While such a distribution is not necessarily inconsistent with the profiles derived here, it is difficult to understand why the DIG emission would be enhanced around individual HII regions, unless the gas becomes optically thin in these regions as well.

5.2. The Diffuse Fraction

The global diffuse fractions of the galaxies presented here, together with those found in other galaxies, show a striking similarity to each other. If the amount of Lyc photons produced in HII regions were the only governing factor in determining the properties of the DIG, then galaxies with low global star formation rates, such as the SMC, would be expected have different DIG properties than more actively star–forming galaxies, such as NGC 7793 presented here. The constancy of the diffuse fraction among galaxies of differing Hubble types and star formation rates suggests a conspiracy between the level of star formation and some additional factor, with the result that the fraction of photons which escape from discrete HII regions is more or less constant from galaxy to
A similar conclusion can also be reached from inspection of the radial variation of the diffuse fractions in NGC 247 and NGC 7793. Since the surface brightness of Hα emission from HII regions, hence Lyc production, decreases with increasing galactocentric radius, one might expect less diffuse emission to be present in the outermost parts. Instead, the diffuse fraction in NGC 247 is constant across the disk, while the diffuse fraction in NGC 7793 increases with galactocentric radius. WB94 also found a relatively constant diffuse fraction in each of the fields they surveyed in M31. This behavior suggests that the additional factor which regulates Lyc photon leakage in galaxies is one which has some radial dependence within disks, and one which varies from galaxy to galaxy.

This additional factor may be the HI column density; the (qualitative) agreement between the observed radial profiles of the diffuse fraction and the predictions of the Dove and Shull models lend support for this idea. Dust may also play an important role in regulating the fraction of Lyc photons which can leak over large distances. NGC 7793 is known to have a moderately steep metallicity gradient (Kennicutt, Zaritsky and Huchra 1994), implying more dust per unit gas mass (and per unit star formation rate) in the central regions than in the outer parts. This could result in enhanced absorption of Lyc photons in the central regions, when compared to the outer disk, and provide at least a partial explanation for the trend observed in the diffuse fraction. Furthermore, a higher dust fraction in the central regions would also mean that less of the DIG produced here would actually be observed. A detailed study of the metallicity and extinction in HII regions across the disks of NGC 7793 and NGC 247 is needed to address this issue further.

5.3. Lyc Power Requirements

The minimum Lyc power requirements we have derived for the DIG in NGC 247 and NGC 7793 are huge and pose the greatest challenge to all models for the origin of the DIG. The recent evolutionary synthesis models of Leitherer and Heckman (1995) can be used to place constraints on several possible sources of the ionizing photons. These models may be used to estimate the global star formation rates based on the observed Hα luminosities. We make the assumption that the DIG is powered by star formation, and include its contribution in the total Hα luminosities of the galaxies. Independent estimates of the SFRs, based on the far–infrared luminosities, may then be used as a check on how realistic an assumption this is.

The [NII] and extinction–corrected total Hα (DIG plus HII regions) luminosities were measured to be $4.1 \times 10^{40}$ erg s$^{-1}$ for NGC 7793 and $1.5 \times 10^{40}$ erg s$^{-1}$ for NGC 247. Formula (9) of Leitherer and Heckman (1995) then translates these values into Lyc photon production rates of $3.03 \times 10^{52}$ s$^{-1}$ and $1.10 \times 10^{52}$ s$^{-1}$. These photon production rates correspond to global star formation rates ($M > 1 M_\odot$) of 0.096 $M_\odot$ yr$^{-1}$ for NGC 7793 and 0.035 $M_\odot$ yr$^{-1}$ for NGC 247,
assuming a Salpeter IMF with $M_{\text{upper}} = 100 \, M_\odot$ and solar metallicity (Leitherer and Heckman 1995). It should be noted that metallicity only influences the derived quantities to a small extent. Adopting $M_{\text{lower}} = 0.1 \, M_\odot$ would increase these star formation rates by a factor of 2.5. These values are all tabulated in Table 2.

The integrated infrared luminosities of the galaxies provide an independent estimate of the global star formation rates. Using the measured IRAS fluxes (Rice et al. 1988) and assuming the distances in Table 1, the far infrared luminosities were calculated to be $1.9 \times 10^{42}$ erg s$^{-1}$ for NGC 7793 and $4.5 \times 10^{41}$ erg s$^{-1}$ for NGC 247. From the derivations of Hunter et al. (1989) (their equation 14), these luminosities can be converted into star formation rates of $0.24 \, E^{-1} \, M_\odot$ yr$^{-1}$ for NGC 7793 and $0.06 \, E^{-1} \, M_\odot$ yr$^{-1}$ for NGC 247, where $E$ is a constant of order unity measuring the coupling efficiency between the total power radiated by dust grains and that included in the IRAS–based measurement of $L_{\text{IR}}$. While these calculations are based on different stellar lifetimes than those used in the Leitherer and Heckman models and have several uncertainties, such as the value of the lowest main–sequence stellar mass that significantly contributes to $L_{\text{IR}}$, they agree with the star formation rates calculated on the basis of the total H$\alpha$ luminosities to within a factor of 2. Had we been incorrect to include the H$\alpha$ luminosity of the DIG in our estimate of the star formation rate, we could have expected much larger discrepancies between the rates calculated based on these different methods. Thus, it seems quite reasonable that the DIG is indeed powered by Lyc photons from OB stars.

We can use the set of Leitherer and Heckman (1995) models which are based on a constant SFR to estimate the mechanical energy that is injected into the ISM from Type II supernovae and stellar winds. These models give a mechanical luminosity of $7.6 \times 10^{40}$ erg s$^{-1}$ for NGC 7793 and $2.7 \times 10^{40}$ erg s$^{-1}$ for NGC 247, based on the assumptions mentioned above and using the star formation rates calculated from the H$\alpha$ luminosities (note that these mechanical outputs would be increased by a factor of two if we assumed a Miller–Scalo IMF). These numbers can be compared with the minimum Lyc power required to ionize the DIG, derived in Section 4.4; they fall short by a factor of 2.5 in NGC 7793 and by a factor of 4.4 in NGC 247. If we compare them to the more realistic power requirements, calculated on the basis of the corrected DIG H$\alpha$ luminosities, then they fall short by factors of 3.6 in NGC 7793 and 4.5 in NGC 247. Type I supernovae will provide an additional contribution to the mechanical luminosity, but given the estimates of the relative rates of Type I and Type II supernovae in typical disk galaxies (van den Bergh and Tammann 1992), it is unlikely that this will change the available energy by more than a factor of two. We can thus conclude that supernovae and stellar winds are unable to produce a substantial fraction of the DIG ionization in these galaxies, even assuming that they can transfer their energy to the ISM with 100% efficiency. This result contrasts with that found for the solar neighborhood where the energy from supernovae can almost account for the observed level of DIG ionization (Reynolds 1984).

Despite the fact that OB stars are the only known source of ionizing photons which can easily meet the overall power requirements for the DIG, several unresolved issues remain. As pointed out
by Reynolds (1995), observations of HI clouds suggest that there are 3–4 clouds with \(N_{HI} \sim 3 \times 10^{19} \, \text{cm}^{-2}\) along every 300 pc line of sight near the midplane of the Galactic disk, with the number possibly increasing dramatically towards lower column densities (Kulkarni and Heiles 1987; Dickey and Garwood 1989). Such clouds are expected to present a significant opacity to Lyc photons and should severely limit the distance which photons can travel radially within disks similar to that of our Galaxy. In addition, the recent non-detection of the HeI \(\lambda 5876\) recombination line in the direction of relatively high Galactic DIG surface brightness implies that the local DIG ionization is due to a significantly softer spectrum than that expected from the bulk of the O star population in the solar neighborhood (Reynolds and Tufte 1995). This result implies that either stars of spectral type O8 and later provide most of the ionizing photons for the local DIG, or that some mechanism is in place which effectively softens the radiation from early type O stars.

Late-type O and early B stars account for 24% of the total Lyc photons produced in the solar neighborhood (Vacca, Garmany and Shull 1995), although this number may be an underestimate (e.g. Cassinelli et al. 1995). Assuming this value, and using the Leitherer and Heckman models to predict the total output in Lyc photons for the inferred star formation rates, we can estimate the amount of ionizing luminosity produced by such stars in NGC 7793 and NGC 247. The Leitherer and Heckman models predict total ionizing outputs of \(9.6 \times 10^{41} \, \text{erg s}^{-1}\) in NGC 7793 and \(3.4 \times 10^{41} \, \text{erg s}^{-1}\) in NGC 247. The power from soft Lyc photons produced directly by late-type O and early B stars is then estimated to be \(2.3 \times 10^{41} \, \text{erg s}^{-1}\) in NGC 7793 and \(8.2 \times 10^{40} \, \text{erg s}^{-1}\) in NGC 247. Comparing these numbers with Lyc power requirements in each galaxy, we find that the minimum power requirements can be met in NGC 7793 but not in NGC 247. Both numbers fall short of satisfying the more realistic, corrected Lyc power requirements. Furthermore, these estimates of the soft Lyc power available should be regarded as upper limits since a considerable fraction of the power is consumed in the immediate vicinity of OB stars and hence is not available to ionize ISM over large scales. Our simple calculations indicate that such stars are not likely to produce enough direct soft Lyc radiation to match the power requirements and imply that another mechanism may indeed be needed to produce the soft radiation field which a low HeI/\(\text{H}\alpha\) ratio requires. The absorption and re-emission of Lyc photons as they travel through the ISM could have such an effect; possible sites for this process include ‘chimney’ walls (Norman 1991) and the extended envelopes of HII regions. Detailed maps of the ionization structure in the HII region – DIG transition zone would be required to investigate these issues more thoroughly and to place tighter constraints on the actual soft Lyc power that is available.

Of course, as mentioned above, there are many known sources of Lyc photons, and they all must contribute at some level to produce the widespread ionization of the DIG which is observed.

6. Implications For Measuring Star Formation Rates
Massive star formation in galaxies is commonly traced by Hα emission from HII regions. A crucial issue is whether the contribution of the DIG should be included in this calculation. We have concluded that the large scale radial distribution and intensity of the DIG across NGC 7793 and NGC 247, coupled with the global power requirements, strongly support a picture where the DIG is ionized predominantly by Lyc photons which have leaked from sites of recent star formation. In this scenario, the Hα emission from the DIG is as much related to present-day massive star formation as is the Hα emission detected in discrete HII regions. Failure to count DIG photons when estimating the total Hα emission then leads to an underestimate both of the global and radial variation of SFRs in galaxies, especially in the outermost parts where the DIG contribution is more substantial. For example, had only HII region fluxes been used to calculate the global star formation rates presented in Section 5.3, then the derived rates would have been 29% lower for NGC 7793 and 50% lower for NGC 247.

Most integrated measurements of global SFRs are based on large-aperture Hα photometry, and hence both the HII region and DIG contributions are automatically included. On the other hand, it has been common practice to derive the radial variation of the SFR based on counts of discrete HII regions alone (e.g. Kennicutt 1989). In this case, the exclusion of the DIG component becomes a more serious issue and particularly affects the star formation rates derived for the outer parts of galaxies, where the DIG contribution to the Hα emission is considerable. Kennicutt et al. (1995) also noted the possible importance of counting the DIG in deriving radial star formation rates and raised the crucial issue of how to estimate the location of the origin of the DIG photons. If significant Lyc photon transport occurs within disks, then the location of the recombination photon (traced by Hα emission) may be very different from the location where the Lyc photon originated. Our data are binned in radial bins of size 350 pc (NGC 7793) and 500 pc (NGC 247), typical of the distance which is predicted to trap > 90% of the escaping Lyc photons vertically in the disk of our Galaxy (Dove and Shull 1994). Since 350 pc corresponds to ~ two HI scaleheights in our Galaxy and is a small fraction of an HI scalelength, this suggests that possibly less transport occurs over a similar distance radially within the disk. Thus we expect that less than 10% of the DIG photons in a given bin will have been radially transported from other locations in the disk. As noted earlier, DIG can generally be found at mean distances of ~ 500 pc from bright HII regions; this provides another constraint on the typical scales over which radial transport takes place and is in good agreement with the distance required to produce the appropriate dilution of the Lyc flux from O stars to explain the observed DIG line ratios (e.g. Reynolds 1994). Constraints on the amount of radial photon transport can come from calculating the total Lyc power required per annulus as a function of radius. Both galaxies have almost constant power requirements per annulus across their disks, declining significantly only in the last few bins. Thus, if radial transport were occurring over significant scales, a very large, probably unrealistic fraction of the total Lyc photons would have to be transported.

Figures 7a and b illustrate the variation of Hα surface brightness (proportional to SFR/area), derived on the basis of counting either total Hα emission or only HII region emission, versus
Fig. 7.— (a) Plot of the H\textalpha surface brightness (proportional to SFR/area), derived on the basis of counting both total H\textalpha emission (filled squares) and HII region emission alone (open diamonds), versus the HI surface density for NGC 7793. (b) Same as in (a) for NGC 247.

the HI surface density for each galaxy (Carignan & Puche 1990a; 1990b). Such plots provide information on the physics underlying the star formation law in galaxies. The contribution of molecular hydrogen is not included in these plots. The two estimates of the SFR/area show very different behaviors. The estimates based on HII regions alone show a sharp cut-off at low HI column densities. Such an effect has been interpreted as being the result of a threshold for massive star formation (Kennicutt 1989). This evidence for an abrupt cut-off is not seen in our data when the DIG component is included in determining the star formation rate.

A similar result was found by Ryder and Dopita (1993) in their study of radial surface brightness profiles in a large sample of southern spirals. They noted that H\textalpha scalelengths are on average larger than V and I scalelengths when areal surface photometry is carried out. This result contrasts with that found by Kennicutt (1989), using HII region counts alone, who found that broadband (BVR) scalelengths are generally very similar to H\textalpha scalelengths in galactic disks. Ryder and Dopita (1993) have suggested this discrepancy may be due to the fact that areal surface photometry takes into account a faint, diffuse component of H\textalpha emission which could play an important role in the outer disks of galaxies. In this paper, we find compelling evidence that this is indeed the case.

7. Summary
We have presented a study of the large scale distribution and global energetics of widespread diffuse ionized gas lying outside the boundaries of discrete HII regions, identified from deep Hα images of the nearby Sculptor spirals NGC 247 and NGC 7793. We have separated the total Hα emission into that from discrete HII regions and that from diffuse emission by means of an isophotal cut in surface brightness, corresponding to an emission measure of 80 pc cm$^{-6}$. Most of the Hα emission lying below this value is clearly diffuse and/or filamentary.

Radial and azimuthal intensity distributions of the DIG reveal that it is highly correlated with bright HII regions over both small and large scales. On the scales of a few hundred parsecs, the bright DIG is localised around individual luminous HII regions in frothy, filamentary halos. At faint surface brightnesses, the DIG is ubiquitous, though maintains the overall pattern and extent of the bright star–forming disk. Over larger scales, the DIG has spatial and intensity distributions which closely follow those of the discrete HII regions, and, hence, of the mean level of star formation.

The observed DIG Hα luminosities are considerable and the DIG contributes 50% of the measured total Hα luminosity in NGC 247 and 29% in NGC 7793. These values are lower limits derived by assuming that the intensity of the DIG overlying discrete HII regions is zero. More realistic values of the diffuse fractions, calculated assuming that DIG fills the entire area of the elliptical annuli used, are 53% in NGC 247 and 41% in NGC 7793. These values are remarkably similar to the global diffuse fractions found in other actively star–forming galaxies, which span a range of morphological types and star formation rates. This unexpected result suggests some global regulation of the fraction of photons which can leak from HII regions and are available to ionize the ISM over large scales. The radial variation of the diffuse fraction shows an increase across the disk of NGC 7793 and is relatively constant across the disk of NGC 247, despite the declining star formation rate per unit area (ie. Lyc production rate) with increasing radius. This behaviour suggests that the additional factor which regulates photon leakage from HII regions is one which has some radial dependence. The qualitative agreement between our observations and the predictions of the Dove and Shull (1995) models for photoionization of the DIG suggest that this factor may be the HI column density. We note the role that dust might play in regulating photon leakage in galaxies. More detailed metallicity gradients are required for these galaxies in order to further investigate this issue.

The integrated minimum Lyc powers required to sustain the DIG in these galaxies are enormous and place tight constraints on the source of the ionizing photons. Only massive star formation can easily satisfy the power requirements, with the mechanical luminosity from supernovae and stellar winds falling short by more than a factor of two. This result contrasts with that found for the local Galactic DIG where the energy from supernovae can almost account for the observed level of ionization. In view of the new constraints imposed on the origin of the DIG photons from the non–detection of the HeI$\lambda$5876 recombination line in the Galaxy, we estimated the Lyc power supplied by stars of spectral type O8 and later. The available power falls short of realistic estimates of the required Lyc power, implying that direct radiation from such stars alone
cannot account for the entire ionization of the DIG. This suggests that either some mechanism is in place which softens the radiation field of early O stars, which produce the bulk of the Lyc photons, or that the photons which ionize the DIG come from a variety of sources, all contributing at some level to produce the widespread ionization which is observed.

Our results strongly support an interpretation of the DIG as being due to Lyc photon leakage from discrete HII regions. In such a scenario, the DIG is a direct product of recent massive star formation and its contribution to the Hα emission line flux of the galaxy should be included in order to derive accurate star formation rates. We have illustrated the importance of taking the DIG into account when studying the correlation between star formation rate per unit area and HI gas surface density. If HII regions alone are used to trace the star formation rate per unit area, then these plots show a sharp cut–off in star formation activity at low HI column densities, commonly interpreted as being the result of a threshold for massive star formation (Kennicutt 1989). This evidence for an abrupt cut–off is not seen in our data when the DIG component is included in determining the star formation rate per unit area.

We thank Piero Rosati for many useful discussions during the course of this work, both scientific and technical, and Tim Heckman, Colin Norman and Gerhardt Meurer for commenting on an earlier draft of this paper. The anonymous referee provided comments which helped us improve the presentation of our results. We thank the staff of Cerro Tololo Inter–American Observatory for their excellent support. AMNF acknowledges receipt of an Amelia Earhart Fellowship awarded by the Zonta International Foundation. This research has been supported in part by NASA grant NAGW–2892. The Center for Particle Astrophysics is funded by the NSF.
REFERENCES

Abbott, D. C. 1982, ApJ, 263, 732
Carignan, C. 1985, ApJS, 58, 107
Carignan, C. & Puche, D. 1990a, AJ, 100, 641
Carignan, C. & Puche, D. 1990b, AJ, 100, 394
Cassinelli, J. P. et al. 1994, ApJ, 438, 932
Davies, R. D., Elliot, K. J. & Meaburn, J. 1976, MNRAS, 81, 89
Dettmar, R. J. 1992, Fund. Cosmic Physics, 15, 143
Dettmar, R. J. & Schulz, H. 1992, A&A, 254, 25
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. R., Buta, R. J., Paturel, G., & Fouqué, P.
1991, Third Reference Catalogue of Bright Galaxies (Springer-Verlag, New York)
Dickey, J. M. & Garwood, R. W. 1989, ApJ, 341, 201
Dömgorgen, H. & Mathis, J. S. 1994, ApJ, 428, 647
Dove, J. B. & Shull, J. M. 1994, ApJ, 430, 222
Elmegreen, B. G. 1987, ApJ, 312, 626
Hester, J. J. & Kulkarni, S. R. 1990, in The Interstellar Medium in External Galaxies, edited by
D. Hollenbach & H. Thronson (NASA CP-3084), p. 288
Hunter, D. A., Gallagher, J. S., Rice, W. L. & Gillet, F. C. 1989, ApJ, 336, 152
Hunter, D. A. & Gallagher, J. S. 1990, ApJ, 362, 480
Hunter, D. A. & Gallagher, J. S. 1992, ApJ, 391, L9
Hunter, D. A. 1994, AJ, 108, 1658
Kennicutt, R. C. 1984, ApJ, 287, 116
Kennicutt, R. C. 1988, ApJ, 334, 144
Kennicutt, R. C., Edgar, B. K. & Hodge, P. W. 1989, ApJ, 337, 761
Kennicutt, R. C. 1989, ApJ, 344, 689
Kennicutt, R. C., Bresolin, F., Bomans, D. J., Bothun, G. D. & Thompson, I. B. 1995, AJ, 109, 594
Kulkarni, S. R. & Heiles, C. 1988, in Galactic and Extragalactic Radio Astronomy, edited by
G. Verschuur & K. I. Kellerman (Springer, New York), p. 95
Lehnert, M. D. & Heckman, T. M. 1994, ApJ, 426, L27
Leitherer, C. & Heckman, T. M. 1995, ApJS, 96, 9
Miller, W. W. & Cox, D. P. 1993, ApJ, 417, 579
Monnet, G. 1971, A&A, 12, 379
Norman, C. A. 1991, in The Disk–Halo Connection in Galaxies, IAU Symposium No. 144, edited by H. Bloemen (Kluwer, Dordrecht), p. 337
Patel, K. & Wilson, C. D. 1995, ApJ, 451, 607
Rand, R. J., Kulkarni, S. R. & Hester, J. J. 1990, ApJ, 352, 1
Raymond, J. C. 1992, ApJ, 384, 502
Reynolds, R. J., Roesler, F. L., Scherb, F., & Boldt, E. 1971, in The Gum Nebula and Related Problems, edited by S. P. Maran, J. C. Brandt & T. P. Stecher (NASA SP-332), p. 169
Reynolds, R. J. 1984, ApJ, 282, 191
Reynolds, R. J. 1990, ApJ, 348, 153
Reynolds, R. J. 1991 in The Disk–Halo Connection in Galaxies, IAU Symposium No. 144, edited by H. Bloemen (Kluwer, Dordrecht), p. 67
Reynolds, R. J. 1993, in Back to the Galaxy, AIP Conf. Proc. No. 278, edited by S. S. Holt & F. Verter, p. 156
Reynolds, R. J. & Tufte, S. L. 1995, ApJ, 439, 17
Reynolds, R. J. 1995, in The Physics of the Interstellar Medium and Intergalactic Medium, A.S.P. Conf. Ser. Vol. 80, edited by A. Ferrara, C. F. McKee, C. Heiles and P. R. Shapiro, p. 388
Rice, W., Lonsdale, C. J., Soifer, B. T., Neugebauer, G. & Kopan, E. L. 1988, ApJS, 68, 91
Ryder, S. D. & Dopita, M. A. 1994, ApJ, 430, 142
Schild, R. E. 1977, AJ, 82, 337
Sciama, D. W. 1990, ApJ, 364, 549
Sciama, D. W. & Salucci, P. 1990, MNRAS, 247, 506
Scowen, P. A., 1992, Ph. D. Thesis, Rice University.
Slavin, J. D., Shull, J. M. & Begelman, M. C. 1993, ApJ, 407, 83
Stone, R. P. S. & Baldwin, J. A. 1983, MNRAS, 204, 347
Tenorio-Tagle, G. & Bodenheimer, P. 1988, ARA&A, 26, 145
Vacca, W. D., Garman, C. D. & Shull, J. M. 1995, preprint.
van den Bergh, S. & Tammann, G. A. 1991, ARA&A, 29, 363
Veilleux, S., Cecil, G. & Bland-Hawthorn, J. 1995, ApJ, 445, 152
Walterbos, R. A. M. & Braun, R. 1994, ApJ, 431, 156 (WB94)
Webster, B. L. & Smith, M. G. 1983, MNRAS, 204, 743

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FIGURE CAPTIONS

Fig.1 – (a) Hα continuum–subtracted image of NGC 7793 displayed at high contrast to show only the cores of bright HII regions. North is up and east is to the left.
(b) Hα continuum–subtracted image of NGC 7793 displayed at low contrast to show the diffuse ionized gas emission.
(c) Hα continuum–subtracted image of NGC 247 displayed to show the cores of bright HII regions. North is up and east is to the left.
(d) Hα continuum–subtracted image of NGC 247 displayed to show the diffuse ionized gas emission.

Fig.2 – (a) Subsection of NGC 7793 illustrating the DIG. Pixels with EM > 80 pc cm$^{-6}$ have been masked out (white).
(b) As in (a) but for NGC 247

Fig.3 – (a) Plot of the azimuthal variation of uncorrected Hα +[NII] surface brightness at four radii in NGC 7793. The radii correspond to 0.1R$_{25}$, 0.3R$_{25}$, 0.6R$_{25}$ and 0.9R$_{25}$. The width of each radial bin is 250 pc and the data are azimuthally binned into 2° sectors.
(b) As in (a) but for NGC 247

Fig.4 – (a) Deprojected radial profile of the total Hα surface brightness (solid line), the Hα surface brightness derived by counting HII regions alone (dashed–dotted line) and the Hα surface brightness of the DIG (dashed line) in NGC 7793. The optical radius (R$_{25}$) is indicated.
(b) As in (a) but for NGC 247

Fig.5 – Radial variation of the diffuse fraction for NGC7793 (left) and NGC247 (right).

Fig.6 – Minimum power per unit area required to maintain the DIG across the disk of each galaxy. The dotted line indicates the value derived for the solar neighborhood (Reynolds 1984).

Fig.7 – (a) Plot of the Hα surface brightness (proportional to SFR/area), derived on the basis of counting both total Hα emission (filled squares) and HII region emission alone (open diamonds), versus the HI surface density for NGC 7793.
(b) Same as in (a) for NGC 247.
|                  | NGC 7793 | NGC 247 | Reference |
|------------------|----------|---------|-----------|
| Morphological type | SA(s)d   | SAB(s)d | 1         |
|                  | 23$^h$ 57$^m$ 49.5$^s$ | 00$^h$ 47$^m$ 08.7$^s$ | 1         |
|                  | $-32^o$ 35' 24.0'' | $-20^o$ 45' 38'' | 1         |
| Adopted Dist. (Mpc) | 3.38    | 2.53    | 2         |
| $i$              | 53.7     | 75.4    | 2         |
| $R_{25}$         | 5.1' = 5.0 kpc | 10.0' = 7.3 kpc | 2         |
| $R_{Holm}$       | 6.1' = 5.9 kpc | 12.1' = 8.8 kpc | 2         |
| $M_B$            | -18.3    | -18.0   | 2         |
| $L_B$            | $3.1 \times 10^9$ L$_\odot$ | $2.4 \times 10^9$ L$_\odot$ | 2         |
| B-V              | 0.54     | 0.56    | 1         |

References for Table 1.

(1) de Vaucouleurs et al. (1991); (2) Carignan (1985)
### Table 2. Global Energy Budget

|                          | NGC 7793                        | NGC 247                        |
|--------------------------|---------------------------------|--------------------------------|
| Observed $L_{H\alpha}(\text{DIG})$ | $1.2 \times 10^{40}$ erg s$^{-1}$ | $7.5 \times 10^{39}$ erg s$^{-1}$ |
| Corrected $L_{H\alpha}(\text{DIG})^{1}$ | $1.7 \times 10^{40}$ erg s$^{-1}$ | $7.9 \times 10^{39}$ erg s$^{-1}$ |
| $L_{H\alpha}(\text{Total})$ | $4.1 \times 10^{40}$ erg s$^{-1}$ | $1.5 \times 10^{40}$ erg s$^{-1}$ |
| SFR$_{H\alpha}^{2}$ | 0.24 M$_\odot$ yr$^{-1}$ | 0.09 M$_\odot$ yr$^{-1}$ |
| SFR$_{FIR}^{3}$ | $0.24E^{-1}$ M$_\odot$ yr$^{-1}$ | $0.06E^{-1}$ M$_\odot$ yr$^{-1}$ |
| Minimum $L(\text{Lyc})_{\text{required}}^{4}$ | $1.9 \times 10^{41}$ erg s$^{-1}$ | $1.2 \times 10^{41}$ erg s$^{-1}$ |
| Corrected $L(\text{Lyc})_{\text{required}}^{5}$ | $2.7 \times 10^{41}$ erg s$^{-1}$ | $1.25 \times 10^{41}$ erg s$^{-1}$ |
| $L(\text{mech})_{\text{available}}^{6}$ | $7.6 \times 10^{40}$ erg s$^{-1}$ | $2.7 \times 10^{40}$ erg s$^{-1}$ |
| $L(\text{direct soft Lyc})_{\text{available}}^{7}$ | $2.3 \times 10^{41}$ erg s$^{-1}$ | $8.2 \times 10^{40}$ erg s$^{-1}$ |

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1. Assumes DIG fills each elliptical annulus at the mean level measured.
2. Assuming a Salpeter IMF with $M_{\text{lower}}=0.1$ M$_\odot$ and $M_{\text{upper}}=100$ M$_\odot$.
3. Assuming the same IMF as above and with $E \sim 1$.
4. Based on the observed $L_{H\alpha}(\text{DIG})$.
5. Based on the corrected $L_{H\alpha}(\text{DIG})$.
6. From the Leitherer & Heckman (1995) models.
7. Estimated Lyc produced by stars of type O8 and later, assuming Vacca et al. (1995) numbers.