On the Structure and Morphology of the ‘Diffuse Ionized Medium’ in Star-Forming Galaxies

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ABSTRACT

Deep Hα images of a sample of nearby late-type spiral galaxies have been analyzed to characterize the morphology and energetic significance of the “Diffuse Ionized Medium” (DIM). We find that the DIM properties can be reasonably unified as a function of relative surface brightness ($\Sigma/\bar{\Sigma}$, where $\bar{\Sigma}$ is the mean Hα surface brightness within regions lying above a fixed very faint isophotal level). We measured the images down to this common isophotal limit and constructed a fundamental dimensionless surface-brightness distribution function that describes the dependence of the area (normalized to total area) occupied by gas with a given relative surface brightness ($\Sigma/\bar{\Sigma}$). This function determines both the flux and area contribution by the DIM to global values. The function is found to be almost the same at high surface brightness ($\Sigma/\bar{\Sigma} \gtrsim 1$) and less similar for $\Sigma/\bar{\Sigma} \lesssim 1$. We show the universal distribution function at high surface brightness can be understood as a consequence of the general properties of HII regions including their Hα luminosity function and exponential radial brightness profiles. We suggest that relative surface brightness (rather than an absolute value) is a more physically-meaningful criterion to discriminate the DIM from HII regions. The use of the dimensionless distribution function to quantify the DIM is consistent with the fundamentally morphological definition of the DIM as being ‘Diffuse’. The difference in the distribution function from galaxy to galaxy at low surface brightness quantifies the different prominence of the DIM in the galaxies. This variation is found to be consistent with results from other complementary ways of determining the DIM’s global importance. The variation of the DIM among the galaxies that is indicated by the distribution function is small enough to guarantee that the fractional contribution of the DIM to the global Hα luminosity in the galaxies is fairly
constant, as has been observed. The *continuous* transition from HII regions to the DIM in the distribution function suggests that the ionizing energy for the DIM mainly comes from HII regions, consistent with the “leaky HII regions model”.

*Subject headings:* Galaxies: ISM - ISM: structure - HII regions - galaxies: spiral
1. INTRODUCTION

The interaction/feedback between massive stars and the interstellar medium has been a key problem in understanding star formation and the evolution of galaxies. The physical state, dynamics and composition of the multiphase ISM are greatly influenced by the energy and material deposited by stars. The most recently discovered major component of the ISM is the widespread diffuse ionized medium (DIM). This gas, first discovered as the ‘Reynolds Layer’ in our Galaxy (see, e.g. Reynolds 1990 for a review), and then in other late-type spiral (e.g. Ferguson et al. 1996; Hoopes et al. 1996; Wang, Heckman & Lehnert 1997–hereafter WHL) and irregular galaxies (e.g. Martin 1997), is probably one of the ISM components that is most closely related to the feedback process. The observed properties of the DIM are characterized by relatively strong low ionization forbidden lines compared to normal HII regions, a low surface brightness, a rough spatial correlation with HII regions, and a significant contribution ($\sim$20%–40%) to the global H$\alpha$ luminosity. The importance of this least studied ISM component is further emphasized by its likely ubiquity in galaxies ranging from normal spirals to starbursts (Lehnert & Heckman 1994; Wang, Heckman & Lehnert 1998). Studying the DIM, whose properties are largely determined by the ionizing radiation and/or mechanical energy supplied by massive stars, will help us to better understand the interaction between star forming regions and the ISM.

The existing observations raise many interesting questions about the physical and dynamical state of the DIM that are still to be answered. The energy required to power the DIM suggests that the gas either soaks up nearly 100% of the mechanical energy supplied by supernovae and stellar winds, or the topology of the interstellar medium must allow a substantial fraction of the ionizing radiation produced by massive stars to escape HII regions and propagate throughout much of the disk. The emission lines from the DIM show relatively large linewidths compared to the HII regions and in some cases, the
high ionization lines (e.g. [OIII]λ5007) have larger linewidths than the low ionization lines (WHL). This raises the intriguing possibility that the DIM is not a uniform gaseous phase, and that different heating mechanisms may play roles in different parts of the DIM. WHL found there is a dominant, quiescent phase of the DIM which contributes more than 80% of total Hα emission of the DIM and is likely photoionized by Lyc photons leaking from HII regions, and a disturbed DIM component which is responsible for the broadened high-ionization line emission and is probably heated mechanically.

There are several pieces of evidence that favor photoionization of the quiescent DIM by radiation leaking from HII regions (cf. WHL). Firstly, radiation from massive stars is the only ionization source that can comfortably provide the energy requirements of the DIM. Secondly, there is a morphological correspondence between the DIM and giant HII regions (Hoopes et al. 1996; Ferguson et al. 1996; WHL). Thirdly, the transition from HII regions to the quiescent DIM is continuous in physical and dynamical properties (e.g. WHL; Martin 1997). Fourthly, the relatively narrow emission-lines of the quiescent DIM (WHL) argue against mechanical heating as the dominant ionization source. Finally, photoionization models can readily explain the relative intensities of the low-ionization lines in the quiescent DIM. These arguments also rule out the possibility of other proposed energy sources for the DIM, such as the decay of neutrino dark matter (Schiama 1990), which do not predict a relationship between the DIM and HII regions. It is thus essential to study the DIM in conjunction with the HII regions that it surrounds.

An additional mystery about the relation between the DIM and HII regions is the relatively constant fractional contribution of the DIM to the global Hα luminosity. Many studies show that roughly 20–40% of the Hα emission is from the diffuse gas, for different types of galaxies (ranging from early-type spiral [Sb] to irregular) and different inclinations (Hunter & Gallagher 1990; Kennicutt et al. 1995; Ferguson et al. 1996; Hoopes et al. 1996);
this is inspite of the fact that a variety of methods were adopted to isolate the DIM. This roughly constant DIM fraction suggests the DIM correlates with HII regions and therefore the star formation process in a fundamental way.

A crucial problem in the studies of the DIM is how to separate the DIM from higher surface brightness gas (HII regions). Because of their spatial correlation, the DIM seems more like an extension of HII regions whose boundaries are not easy to define. A simple approach is to set an absolute surface brightness limit for the DIM. This method can not deal well with the case in which mean surface brightness of the DIM varies across galactic disks (e.g. Hoopes et al. 1996) or from galaxy to galaxy. Such variations will occur due to differences in the heating rate of the DIM. A criterion based on the morphology of the gas is more important in this respect, because the diffuse nature of the DIM is more fundamental than any seemingly arbitrary absolute surface brightness. However, so far no such morphology-based methods have been developed to isolate the DIM.

In order to better understand the DIM, it is therefore very useful to conduct a thorough investigation of its morphology, its relation with and differentiation from HII regions, and its global importance. In this paper we present our analysis of Hα images of a sample of 7 of the nearest, largest, and brightest normal late-type galaxies to address these issues. The sample is selected on the basis of Hubble type (Sb and later), proximity (closer than 10 Mpc), large angular size (> 10 arcmin), and relatively face-on orientation (inclination < 65°), and includes M 51, M 81, M 101, NGC 2403, NGC 4395, NGC 6946 and IC 342. Some general properties of these galaxies are listed in Table 1. Our sensitive Hα images of these galaxies can provide us with crucial information about the structure and global significance of the DIM and, more fundamentally, the common, basic properties shared by the DIM in star-forming galaxies.
2. OBSERVATIONS AND DATA REDUCTION

Most of the relevant observational information has been presented by WHL. The only change in our imaging data is that we now address the complete sample including two new objects (NGC 6946 and IC 342) which were not discussed by WHL. This imaging analysis is part of a larger project that investigates the DIM in both the Hα images and longslit spectra. Therefore in the following sections, we sometimes refer to the spectra, information about which can be found in WHL, Wang, Heckman, & Lehnert (1998), and Wang (1998).

Our imaging data were obtained during February 23-28, 1995 and November 1-2, 1994, with the 0.9 meter telescope at KPNO. We used a Tek 2048×2048 CCD with a 0.68″ pixel size, yielding a field of view of 23.2×23.2 arcmin². The Hα filter had a FWHM of 26Å and was centered on 6562Å. Thus, relatively little flux from the [NII]λλ6548,6584 was included in these ‘on band’ images. ‘Off-band’ observations of the continuum were made with a narrow band filter having a FWHM of 85Å centered on 6658Å. Several 1800(600) second exposures were taken through the Hα (continuum) filter for each object.

Data reduction was done using the IRAF package following standard procedures. Images were bias-subtracted first and flat-fielded with a master flat combined from a set of many dome flats. Sky-subtracted images were then geometrically rectified to align Hα on-band images with the off-band images.

The limit to the detection of diffuse, low-surface-brightness Hα emission in our data is set by the accuracy with which the contribution of continuum emission in the on-band image can be subtracted (since the DIM Hα emission has a small equivalent width). In this regard, the images are inferior to long-slit spectra with a spectral resolution matched to the intrinsic line-widths of the Hα emission-lines (to maximize the contrast of the lines against the continuum). We have therefore done this continuum subtraction in our images by scaling the off-band image such that difference image agreed with the distribution of the
Hα surface brightness in the long-slit spectra (as presented by WHL and Wang 1998) in the region of overlap. The agreement between the two sets of data has been ensured to be better than 10%.

To make this comparison, we first sliced the continuum-subtracted Hα line images in the regions covered by the slit in the relevant spectral observations. We then reproduced the spatial profile of Hα surface brightness variation in the same regions and compared it to that shown by the spectra (see WHL and Wang 1998 for details about making similar profiles for the Hα line in the spectra). By making small iterative adjustments to the scaling factor for the off-band image, we were able to get good matches of the profiles between the imaging and spectral data. This allowed us to obtain the final, most reliable continuum-subtracted Hα images.

Photometric Hα imaging observations of giant HII regions (Kennicutt 1988) in these galaxies (except IC 342) were used to flux-calibrate our images. We have also used our long-slit spectra to check for consistency, and find that the agreement in Hα flux in the regions of overlap is better than 10% for NGC 2403, NGC 6946, NGC 4395 and M 101 and 30% for M 51. For IC 342, we used the flux scale determined from our long-slit spectra of Hα, which were taken under photometric conditions, to flux-calibrate the image. The result was then checked against the flux calibration provided by narrow-band images of standard stars. We find a consistency better than 30%. This indicates the flux calibration for the IC 342 image is also reliable.

Internal extinction in the galaxies has not been corrected for. For most of the galaxies, foreground Galactic extinction is not important. From the HI survey by Stark et al. (1992), we derived the Galactic extinction in magnitudes at Hα \( A_{H\alpha} \) (Table 1). The Galactic HI column densities are substantial only in the directions toward NGC 6946 and IC 342: they imply \( A_{H\alpha} \) to be 1.63 for IC 342 and 1.43 for NGC 6946. These values are consistent with
the previous measurements of $E_{B-V}$ within the uncertainty: $A_{H\alpha}$ was found to be 1.8 for IC 342 (McCall 1989) and 1.0 for NGC 6946 (Burstein & Heiles 1984) if $A_{H\alpha} = 2.5 E_{B-V}$. Using our values, the fluxes at $H\alpha$ for these two galaxies would be raised by a factor of $\sim 4$ after foreground extinction correction.

3. RESULTS

The $H\alpha$ images of our sample galaxies are shown in Figure 1. The images have been smoothed with a box having a size of $2'' \times 2''$. A faint, diffuse gas component can be seen throughout the disks of these galaxies. The detection of extremely faint gas is affected by the uncertainty of continuum subtraction of the images. But as discussed by WHL and Wang (1998), the wide spatial distribution of the DIM has also been confirmed by our spectra, which have a higher sensitivity. The diffuse gas is preferentially located along the edges of spiral arms and around isolated HII regions, as is generally the case for the DIM (e.g. Ferguson et al. 1996; Hoopes et al. 1996). For M 81, the diffuse gas component within a radius of 2–3$''$ from the nucleus seems to not be associated with any prominent star-forming regions and is probably different in nature from the DIM seen elsewhere. The LINER-type nucleus in this galaxy or a population of hot post-main-sequence low-mass stars may play a role in energizing the gas (Devereux, Jacoby, & Ciardullo 1995, 1996).

3.1. Growth Curves

A simple approach to study the DIM contribution to the total $H\alpha$ flux is to plot the integrated flux against a surface brightness cutoff below which the flux is integrated (a ‘growth curve’). Instead of clipping out discrete HII regions before smoothing the image, as done by WHL in order to avoid contamination of bright HII regions to the DIM, here we
use a more straightforward method of simply smoothing the raw image with a $2'' \times 2''$ box and constructing a growth curve. This method results in slight differences from the results in WHL, but the robust pattern is still the same.

Because the typical surface brightness of the DIM ($\sim 10$ pc cm$^{-6}$) is comparable to the noise of the background of the resulting smoothed images, we determined the flux from these images by integrating from $-3\sigma$ below the mean background of the images up to a given surface brightness level. We repeated this process over a range of surface brightness, starting at a level of $3\sigma$ above the background of the smoothed images. This minimum surface brightness level corresponds to an emission-measure (foreground extinction corrected) of $55$ pc cm$^{-6}$ for IC 342 and NGC 6946, $30$ pc cm$^{-6}$ for M 51 and M 101, $10$ pc cm$^{-6}$ for M 81 and NGC 2403, and $20$ pc cm$^{-6}$ for NGC 4395. The depths of the images do not significantly affect the overall result. Figure 2 thus shows the fraction of the total H$\alpha$ flux contributed by gas below a given surface brightness (emission measure). The data for NGC 6946 and IC 342 in Figure 2 have been corrected for foreground Galactic extinction (see above).

There are four effects that should be noted when interpreting Figure 2. First, the light from HII regions, scattered by the optics in the telescope and camera and by the dust in the galaxies, has not been corrected for. Hoopes et al. (1996) showed that this correction is minor for their sample galaxies. Furthermore, the emission-line ratios of the DIM are significantly different from that of typical HII regions in these galaxies (WHL; Wang 1998). No scattering processes can account for this difference. Thus, scattered light can not dominate the DIM flux and we do not consider this effect here. Second, a more reliable determination of the DIM contribution should include a correction of the missed

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Throughout the paper we convert surface brightness to emission measure assuming an electron temperature of $10^4$ K. $5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ corresponds to $25$ pc cm$^{-6}$. 
diffuse gas flux projected on top of regions of higher surface-brightness (HII regions). A simplified method of making this correction (by assuming the diffuse gas in the clipped-out regions has the mean surface brightness level measured elsewhere, e.g. Ferguson et al. 1996; Hoopes et al. 1996) may increase the DIM fraction significantly, especially for low cut-off levels. At 50 pc cm$^{-6}$, the correction factor may be up to 2 (Hoopes et al. 1996). Third, for the purpose of our study, we did not indicate the uncertainty in continuum subtraction in Figure 2. Based on the comparison of our spectra and images, this uncertainty is minor at the relevant levels of emission measure in most cases, and will not alter the essential behavior of the growth curve. M 101 is the only object whose growth curve is relatively uncertain at low surface brightness (< 100 pc cm$^{-6}$) as caused by continuum subtraction. This is mainly due to two reasons. The image of M 101 is almost filled by the galaxy itself, making it hard to determine a proper background level to subtract. In addition, the DIM in M 101 is less prominent compared to the DIMs in the other galaxies so the S/N ratio for the measurement of the M 101 DIM is relatively poor. Fourth, no internal extinction correction has been applied. In a situation in which HII regions suffer more average extinction than the DIM, the intrinsic DIM fraction should drop accordingly. Because of the small EQWs of the H$\alpha$ and H$\beta$ emission lines in the DIM, we were not able to accurately determine the extinction for the DIM using the Balmer decrement from our spectra (see WHL and Wang 1998 for the spectra).

The growth curves shown in Figure 2 vary among our sample galaxies. In M 51, M 101, NGC 2403, NGC 6946 and IC 342 the flux contribution of the DIM is small relative to that in NGC 4395 and M 81. We verified that the high DIM fraction in M 81 is not due to the prominent diffuse gas component in the inner disk or bulge. To do this test, we masked out a circular region within a radius of 2.5$'$ from the nucleus and constructed the growth curve again. The result showed little difference from that in Figure 2. Thus, the high fraction of the DIM contribution is purely due to the fact that the DIM component in
M 81 is intrinsically prominent throughout the galaxy.

3.2. The Surface-Brightness Distribution Function

Although we (and others) have defined the DIM in terms of a surface-brightness criterion, the D in DIM stands for ‘Diffuse’. Thus, the information on the areal coverage of low Hα surface brightness gas is as important as the flux contribution from the same gas. We make the observations that both the areal and flux contributions from the gas at certain Hα surface brightness levels are determined uniquely by a distribution function \( A(\lg \Sigma) \) that describes the number of pixels occupied by gas with Hα surface brightness within an interval of \( d\lg \Sigma \) centered at \( \lg \Sigma \). It is therefore worthwhile to construct this function to quantify the ‘diffuseness’ of the DIM.

Since we can only measure the area occupied by gas with a given surface brightness down to the detection limit in an image (as characterized by \(+3\sigma\) above the background) and our images have slightly different sensitivities, we chose a common value for this minimum \( \Sigma \), which is no less than \(+3\sigma\) above the background in the relevant images. We have smoothed the images with a \( 4'' \times 4'' \) box before measuring the area at different surface brightness levels. This smoothing with a larger box allows us to measure down to a minimum surface brightness limit that is half as high as the limits given in §3.1 for a \( 2'' \times 2'' \) box smoothing. We then chose a common depth corresponding to a surface brightness of \( 3 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \) (an emission measure of 15 pc cm\(^{-6}\)) for M 51, M 81, M 101, NGC 2403 and NGC 4395, and \( 6 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \) (an emission measure of 30 pc cm\(^{-6}\)) for NGC 6946 and IC 342 after foreground extinction correction. The images of NGC 6946 and IC 342 have poorer sensitivities due to foreground extinction, so we set a higher surface brightness limit for them. This procedure removes the arbitrary factor of the relative depth of the images.
Following these ideas, we have constructed the distribution function $A(\lg \Sigma)$ in Figure 3. We also measured the area within the galaxy disk lying above the minimum limiting surface brightness (see above) and the mean surface brightness $\bar{\Sigma}$ of H$\alpha$ within this area. The area actually used constitutes about 10\%–40\% of the total disk area lying within the galaxy’s 25 B mag arcsec$^{-2}$ isophote, and is illustrated in Figure 4 for M 51 and M 101. These measured area and $\bar{\Sigma}$ (as listed in Table 2) were used respectively to scale $A$ and $\Sigma$ when plotting the distribution function. The purpose of such a scaling is to eliminate any galaxy-dependent factors in the relation between $A$ and $\Sigma$, and thus allow meaningful comparisons between galaxies with very different surface areas or mean surface-brightnesses. Note that, unlike what we did for the growth curves, we now exclude the data with surface brightness between $-3\sigma$ of background and our adopted minimum isophotal limit. The reason is that the morphological properties of the data near the noise level of the images is not well defined. For instance, in M 101 the area above the isophotal limit including both the diffuse gas and HII regions constitutes $\sim$10\% of the total disk area in contrast to $\sim$35\% for M 51 (Table 2 and Figure 4). This difference in the projected fractional area of bright emission-line gas is likely related to arbitrary factors such as different inclination angles of the two galaxies (compare 64$^\circ$ for M 51 and 17$^\circ$ for M 101). When measuring the mean surface brightness and covering area of the DIM, it is then meaningful to only use the area with a surface brightness above the detection limit.

Figure 3 shows the curves lie along almost the same locus, especially in the regime of $\Sigma/\bar{\Sigma} \geq 1$, regardless of objects. We infer that the curves at high surface brightness can be approximately characterized by an universal function

$$\frac{A(\lg \Sigma)}{A_{tot}} = F\left(\frac{\Sigma}{\bar{\Sigma}}\right)$$  \hspace{1cm} (1)

At lower surface brightness ($\Sigma/\bar{\Sigma} \lesssim 1$), the curves start to diverge, i.e. the distribution functions for M 51, M 101, NGC 2403, NGC 6946 and IC 342 have shallower faint-end
slopes compared to those of M 81 and NGC 4395.

The different behavior around the turning point $\Sigma/\bar{\Sigma} \sim 1$ may not be coincidental. We note that $\Sigma = \bar{\Sigma}$ is roughly the dividing point between the DIM and HII regions for two reasons. Firstly, the mean surface brightness we measured (Table 2) roughly matches with the limiting surface brightness that we have previously used to separate the DIM from HII regions in the spectra ($\lesssim 25$ pc cm$^{-6}$ for the DIM and $\gtrsim 100$ pc cm$^{-6}$ for bright HII regions; see WHL). We have shown in our analysis in WHL that these criteria are effective in discriminating between the spectroscopic properties of the DIM and HII regions. Secondly, the universal scaling relation (eq. [1]) for the high surface brightness portion of the distribution function can be derived from the luminosity function and radial brightness profiles of the HII regions (to be discussed in §4.1), and it is therefore solely determined by the physics of high-mass star formation in galaxies. On the other hand, the varying slope of the curve at $\Sigma/\bar{\Sigma} \lesssim 1$ must reflect some intrinsic difference in the DIM properties in galaxies. Therefore, the choice of the mean surface brightness to separate the DIM from the HII regions is sound physically. The advantage of separating the DIM from HII regions based on $\bar{\Sigma}$ is that it takes into account the information about the relative brightness of the emission-line gas in a galaxy (i.e. how bright the gas is typically) instead of only relying on some arbitrary absolute surface brightness criterion.

Although relative surface brightness may be an effective criterion to separate the DIM from HII regions, we point out that the critical value for $\Sigma/\bar{\Sigma}$ does not have to be exactly unity. A general dividing point should be defined as $\Sigma/\bar{\Sigma} = const$ where the constant depends on the value of the minimum surface brightness chosen to delimit the area of the galaxy within which $\bar{\Sigma}$ is determined. That is, more sensitive imaging would allow the value for $\bar{\Sigma}$ to be determined over a greater fraction of the total disk area by making measurements possible in regions with smaller surface brightnesses.
However, we should point out that Figure 3 will still be rather robust to such effects (i.e. the distribution function will be rather insensitive to the value of the common isophotal limit we have adopted for our images). Although $A(\lg \Sigma)$ does not rely on the lowest surface brightness we can measure, the mean surface brightness and total area that we use to scale the plot do depend on it. We found a drop in the lower bound of surface brightness increases the total area significantly but has little impact on the total flux, which is dominated by high surface brightness gas (i.e. HII regions). As a result the area will increase while $\tilde{\Sigma}$ will decrease by roughly the same factor. A shift of the curve in Figure 3 due to change in $\tilde{\Sigma}$ would be approximately compensated by a shift due to total area change. We conclude that the scalability of the distribution function would remain roughly unaffected if the common isophotal limit is varied. This is supported by the similarity of the curves between the low-Galactic-latitude galaxies NGC 6946 and IC 342 (having a higher limiting isophotal level in the images) and the rest of our sample galaxies (Figure 3).

3.3. Integrated Flux and Area Contribution of the DIM

It is worthwhile to examine the growth pattern of not just the Hα flux but also the surface area occupied by the DIM. Thus, we plot the fractional integrated flux against fractional integrated area in Figure 5 using exactly the same surface brightness thresholds and method of measurement as discussed in the previous section. We emphasize that the result in Figure 5 should be completely determined by the surface-brightness distribution function (Figure 3). Because the relative surface brightness is an important parameter to discriminate the DIM from HII regions (see above), we mark the curves with the ratio of $\Sigma/\overline{\Sigma}$ (instead of absolute surface brightness), where the symbols represent successive increases in surface brightness by a factor of 1.25 from $\Sigma/\overline{\Sigma} = 0.4$ (lower left corner) to $\Sigma/\overline{\Sigma} = 3$ (upper-right corner).
Figure 5 shows that the gas with surface brightness from the limiting surface brightness to a given cutoff level of \( \Sigma/\bar{\Sigma} \) contributes to the global H\( \alpha \) flux and covering area in a similar way in all the galaxies, especially at high surface brightness end. There is a difference in the contribution from the fainter gas (the DIM), e.g. at a fixed area fraction, the DIM in M 81 and NGC 4395 contributes more to global flux than the rest of the galaxies.

Figure 2, Figure 3, and Figure 5 are complementary ways of quantifying the contribution of the DIM, and all yield a consistent picture. At high levels of surface-brightness (the HII regions), all the galaxies are very similar. Differences become apparent at low surface-brightnesses, where the DIM is more significant in M 81 and NGC 4395, and less significant in M 51, M 101, NGC 2403, NGC 6946 and IC 342.

Figure 5 graphically illustrates why the measured fractional flux contribution from the DIM is roughly constant (~20%–40%), regardless of Hubble type and other factors (e.g. Ferguson et al. 1996; Hoopes et al. 1996). As \( \Sigma/\bar{\Sigma} \sim 1 \) is probably the point where HII regions and the DIM start to differentiate, we can use this criterion to measure the total DIM contribution to the global H\( \alpha \) flux. We then find from Figure 5 that this contribution converges uniformly at \(~20\%–40\%\) regardless of galaxies. These values have not been corrected for any DIM emission on top of HII regions that might have been missed in the measurement. The fraction is consistent with the measurements from previous studies. Our conclusion is obtained by isolating the DIM based on the distribution function behavior (and therefore fundamentally on H\( \alpha \) morphology) instead of picking an arbitrary absolute surface brightness criterion as others adopted previously. So we have confirmed that the contribution from the DIM to the global flux is indeed \textit{roughly constant} and there exists a physically-meaningful explanation for this: although the slopes of the distribution function of the DIM for different galaxies may vary, they are still similar enough that the flux and area contribution of the DIM converges to a roughly common value. It seems that
the morphological information has been more or less taken into account when choosing
the absolute surface brightness criterion in previous studies. As a result the DIM was
appropriately isolated and the measurements of its flux contribution were roughly correct.

4. DISCUSSION

4.1. The Origin of the Scalable Distribution Function

It is important to understand the underlying physics of the universal distribution
function for HII regions (Σ/\bar{\Sigma} > 1) because it should be physically related to the DIM
properties that we are exploring. Statistically, we need to consider the luminosity function
and size function of HII regions, as these two functions determine the bright end of the
distribution function. The common properties of HII regions are the reason that different
galaxies have approximately the same curve in Figure 3 at high levels of surface brightness,
as we now show.

We model HII regions as isolated (non-overlapping) sources, each of which has an
exponential H\alpha surface brightness profile (e.g. Rozas, Castañeda and Beckman 1998;
Kennicutt 1984)

\[ \Sigma(\theta) = \Sigma_0 e^{-\frac{\theta}{\theta_0}} \]  

where \( \Sigma(\theta) \) is the surface brightness at a given angular distance \( \theta \), \( \Sigma_0 \) is the peak surface
brightness at center, and \( \theta_0 \) characterizes the angular extent of the HII region. \( \Sigma_0 \) is then
related to luminosity \( L \) and \( \theta_0 \) as

\[ \Sigma_0 \propto \frac{L}{\theta_0^2} \]  

There are many studies regarding the luminosity function of HII regions. A simple
power-law usually holds well for many galaxies, while a broken power-law is better for some
others (e.g. Kennicutt, Edgar and Hodge 1989; Oey & Clarke 1998). Here we adopt a
power-law with a constant power index as

\[ N(L) \propto L^{-\beta} dL \]  

(4)

Although the size distribution for HII regions has been known to be exponential

\[ N(\theta_0) \propto \exp(-\theta_0/\theta_c), \text{ e.g. van den Bergh 1981, where } \theta_c \text{ can represent the characteristic angular size spread of the HII regions}, \]

we found the detailed functional dependence of \(N(\theta_0)\) on angular size \(\theta_0\) does not affect our following arguments. So here we only assume there exists a universal \(\theta_0\) distribution of the form

\[ N(\theta_0) d\theta_0 = f(\theta_0) d\theta_0 \]  

(5)

where \(f(\theta_0)\) is some function of \(\theta_0\). In addition, we assume that \(L, \theta_0\) and \(\Sigma_0\) distribute independently. For example, for HII regions with \(\theta_0\) within any given interval the luminosity distribution still follows eq.[4]. Based on eq.[3] and eq.[4], we find the \(\Sigma_0\) distribution obeys a power-law similar to the luminosity function

\[ N(\Sigma_0) d\Sigma_0 \propto \Sigma_0^{-\beta} d\Sigma_0 \]  

(6)

Each source has a contribution to covering area (absolute value in steradian) at a given surface brightness interval of

\[ A(\lg \Sigma) \equiv \frac{dA}{d\lg \Sigma} = 2\pi \theta_0^2 \lg \frac{\Sigma_0}{\Sigma} \]  

(7)

The total amount of \(A(\lg \Sigma)\) contributed by all HII regions in a galaxy is a sum of the contribution by HII regions with a given angular size \(\theta_0\) and a given peak surface brightness \(\Sigma_0\), i.e. it is simply \(A(\lg \Sigma)\) integrated over the ranges of \(\Sigma_0\) and \(\theta_0\). The result of integrating over \(\Sigma_0\) depends on the surface brightness \(\Sigma\) that we are considering, but the integral of \(\theta_0\) does not. Since we know the number distributions of HII regions with angular size (eq.[5]) and peak surface brightness (eq.[6]), it can be shown that the total area for a galaxy at a
given surface brightness is

\[ A_{tot}(\lg \Sigma) = \zeta \int_{\Sigma}^{\Sigma_{\text{max}}} d\Sigma_0 \Sigma_0^{-\beta} \log \frac{\Sigma_0}{\Sigma} \]  

(8)

where \(\Sigma_{\text{max}}\) is the highest peak surface brightness among the HII regions (corresponding to the highest surface brightness we can measure in the image if the sources are not overlapping), which can be assumed to be the same for all galaxies as a good approximation, and \(\zeta\) is a factor containing the result after integrating over \(\theta_0\) and other quantities including distance from the Milky Way, total number of HII regions and characteristic angular size spread \(\theta_c\). Eq.[8] implies that as long as \(\Sigma\) is not comparable to \(\Sigma_{\text{max}}\) (i.e. \(\Sigma \ll \Sigma_{\text{max}}\)), \(A_{tot}(\lg \Sigma) \propto \Sigma^{1-\beta}\). Therefore, the slope of the distribution function tracks that of the luminosity function. For \(\beta = 2 \pm 0.5\) as commonly observed, the range of the distribution function slope encloses the observed values in Figure 3. To be more specific, the dependence of \(A_{tot}(\lg \Sigma)\) on \(\Sigma\) (eq.[8]) is plotted on Figure 3 (solid line, \(\zeta\) is arbitrarily chosen) for which we adopt \(\beta = 2\) and \(\Sigma_{\text{max}}/\bar{\Sigma} = 100\), appropriate for our images.

The model prediction (eq.[8]) fits our data in Figure 3 rather well at high surface-brightness. This implies the universal H\(\alpha\) distribution function for the bright gas is probably just a manifestation of more fundamental HII regions properties such as luminosity function and radial exponential brightness profile (eq.[2] and [4]), which are shared by late-type galaxies and which reflect the underlying star-formation process (e.g. Oey & Clarke 1998). Indeed, eq.[8] dictates that the galaxy-specific \(\zeta\) parameter is cancelled out in the relation between \(A_{tot}(\lg \Sigma)/A_{tot}\) and \(\Sigma/\bar{\Sigma}\), which only depends on the minimal and maximum surface brightness that can be measured. In our case we can regard these limiting surface brightnesses as the same for all sample galaxies. Therefore the \(A_{tot}(\lg \Sigma)/A_{tot}\) vs. \(\Sigma/\bar{\Sigma}\) relation should be universal among galaxies just as observed.

The data at very high surface brightness (\(\Sigma/\bar{\Sigma} \gtrsim 10-20\), Figure 3) show a relatively larger scatter among galaxies. There might be two major reasons for this. Firstly, the
luminosity function can be relatively steep for some galaxies at high L due to the broken power-law (e.g. Kennicutt et al. 1989). It is possible that some of our sample galaxies (e.g. M 51, Kennicutt et al. 1989) may belong to this category. This may result in a steeper slope of the distribution function at high surface brightness. Secondly, as the number of pixels at very high surface brightness is small, statistics may be affected by bad pixels in the images which may be caused by, e.g., residuals of bright stars after continuum subtraction.

4.2. Similarities and Differences in Global DIM Properties Among Galaxies

The universal distribution function of HII regions determines that the emission line nebulae are scalable in surface brightness for $\Sigma > \bar{\Sigma}$. The DIM can then be separated from HII regions according to relative surface brightness ($\Sigma < \text{const} \times \bar{\Sigma}$, where const $\sim 1$ for the limiting surface brightness reached by our images). This criterion is morphologically-based and more meaningful than an absolute surface brightness limit. For galaxies with relatively high average surface brightness, such as starbursts, we expect the DIM surface brightness criterion would be higher too. From comparison of emission-line properties between the normal galaxies discussed in this paper and the Lehnert & Heckman (1995) sample of starbursts, Wang, Heckman and Lehnert (1998) indeed found a DIM component in starbursts that has physical properties similar to those in our normal galaxies, except that the starburst DIM has relatively large absolute surface brightness compared to the DIM in normal star-forming galaxies. In fact, these properties depend only on a relative surface-brightness parameter defined as the surface brightness scaled by the mean surface brightness $\Sigma_e$ within the galaxy’s Hα half light radius $r_e$ (as given in Table 2). Since $\Sigma_e$ is directly proportional to the mean rate of star formation per unit area in the disk, this result is not surprising if we consider the very high star formation rate for the starbursts. This supports our argument here that the relative surface brightness ($\Sigma/\bar{\Sigma}$) is the fundamental
property by which to define the DIM. On the other hand, it is worth noting that the DIM in our normal galaxy sample as defined by the mean surface brightness is still a factor of $10^1$–$10^2$ brighter than the Reynolds layer in our Galaxy, which has a typical emission-measure of only $\sim 1$–5 pc cm$^{-6}$ (Reynolds 1990).

Figure 3 shows that the transition from the high surface brightness gas (HII regions) to the low surface brightness gas (the DIM) is smooth. Therefore there must be a strong relationship between these two otherwise an abrupt change in $A(\lg \Sigma)$ below $\Sigma/\bar{\Sigma} \sim 1$ would be possible. This is consistent with the picture of a smooth transition in physical properties from HII regions to the DIM (WHL) and thus provides additional support for the idea that a unified approach to the study of both the DIM and HII regions is necessary to better understand the DIM.

In the low surface brightness range ($\Sigma/\bar{\Sigma} < 1$), the DIM in some galaxies such as M 101 covers less fractional area than other galaxies at a given $\Sigma/\bar{\Sigma}$. Although we are not able to measure surface brightness far below $\bar{\Sigma}$ to fully assess the variation of the distribution function at low surface brightness end, we find that the data in Figure 3 can all be fitted well with a double power law with a break around $\Sigma/\bar{\Sigma} \sim 1$. While the slope of the distribution function for HII regions ($\Sigma/\bar{\Sigma} > 1$) is approximately the same, it is not the case for the DIM at low surface brightness. Therefore we suggest using the different power-law indices measured for the region of $\Sigma/\bar{\Sigma} < 1$ to indicate the prominence of the DIM in each galaxy. By this criterion, the DIM is most pronounced in M 81 and NGC 4395 (see Table 2).

It is not clear yet what causes the difference in the distribution function of the DIM. It is also possible that as the sensitivity of the images improves, we would find more significant variation in the DIM distribution function at still fainter levels, and as a result more substantial differences in the global properties of the DIM among galaxies.
WHL have tried to characterize the relative importance of the DIM in each galaxy using a measurement that involves only the structure or morphology of the Hα images. We have characterized the ‘DIMness’ of the galaxy by taking the ratio of the mean and the r.m.s. of the Hα surface-brightness (computed for surface brightness $\gtrsim -3\sigma$ of background) within the surface area of the galaxy delimited by the 25 B magnitude per square arcsec isophote. This ratio may be affected by the arbitrary fractional area of regions with surface brightness below the sensitivity level as discussed in §3.2. However, we should expect this mean and r.m.s. ratio to be fairly constant if we only compute it for regions with surface brightness above our common limiting isophotal level instead, as the ‘DIMness’ parameter then solely depends on the distribution function in Figure 3. Indeed, we found that this is the case. Therefore, the ratio of the mean and r.m.s. of the Hα surface brightness may not be a good indicator of the DIM prominence in galaxies.

5. CONCLUSIONS

We have reported on the results from a program to study the structure and morphology of a sample of nearby bright normal late-type galaxies in order to understand the global properties of the DIM. For each of the seven galaxies (NGC 2403, M 81, NGC 4395, M 51, M 101, NGC 6946 and IC 342) we have analyzed deep narrow-band Hα images covering essentially the entire star-forming disk (a field diameter of 23.2 arcmin, or 18 to 53 kpc). These images reach limiting Hα surface-brightnesses of about $2-10 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ (corresponding to an emission measure of about 10–50 cm$^{-6}$ pc).

While the DIM contribution to the global Hα luminosity seems different when the DIM is defined by a given absolute Hα surface brightness, we found that the DIM properties can be reasonably unified as a function of relative surface brightness ($\Sigma/\bar{\Sigma}$, where $\bar{\Sigma}$ is the mean surface-brightness within regions lying above a fixed very faint isophotal level).
The DIM structural properties are described by a fundamental dimensionless ‘distribution function’ that measures the relative area within the galaxy covered by gas at a given relative surface brightness. Indeed, we found this function is very similar for all sample galaxies, especially at high-surface-brightnesses ($\Sigma/\bar{\Sigma} > 1$). We show that this behavior at the high-end is determined only by common HII region properties (the Hα luminosity function and the radial brightness profiles of HII regions).

At lower surface brightness ($\Sigma/\bar{\Sigma} < 1$), the distribution function becomes more diverse, indicating a variation in the DIM prominence among galaxies. In some galaxies (M 51, M 101, NGC 2403, NGC 6946 and IC 342) the distribution function shows a pronounced flattening in power-law slope at the faint-end, indicating a less-conspicuous DIM. In the other galaxies (M81 and NGC 4395), the faint-end slope is steeper (similar to the bright-end slope), and so the DIM is more pronounced. This method and two types of growth curves we made using different methods yield a consistent picture about the global importance of the DIM in our sample galaxies, and they are all valuable in providing complementary information about the DIM.

These results imply that the DIM should be defined by using the relative Hα surface brightness criterion $\Sigma/\bar{\Sigma} \sim 1$ as the boundary between the DIM and HII regions. This criterion is free of factors such as the varying average Hα surface brightness (mean star-formation rate per unit area) from one galaxy to another, and is more physically sound than an absolute surface brightness limit.

The distribution function shows the continuous transition from HII regions to the DIM, suggesting a tight coupling between these two gaseous phases. This is consistent with the idea that the majority of the DIM is photoionized by Lyman continuum photons leaking from HII regions. We found that while some variation in the global importance of the DIM exists among galaxies, a structural (morphological) similarity of the DIMs in our sample
galaxies still exists because of the roughly similar distribution functions. This similarity dictates that the fractional contribution of the DIM to the global H$\alpha$ luminosity in a galaxy is fairly constant (within a factor of $\sim 2$) when the DIM is isolated based on its relative surface brightness.

Our related paper (Wang, Heckman, & Lehnert 1998) extends these ideas about the DIM, and shows that normal star-forming galaxies and starbursts can be unified if the DIM is defined in terms of relative surface brightness. Taken together, our work suggests that the DIM is indeed a fundamental component of all star-forming galaxies, that it is ionized primarily by photons produced by high-mass stars, and that the global structure of the diffuse ISM in star-forming galaxies regulates and/or is regulated by the mean rate of star-formation per unit area in the galaxy.

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Table 1. Galaxy Parameters

<table>
<thead>
<tr>
<th>Object</th>
<th>Hubble Typea</th>
<th>i b</th>
<th>D(Mpc)c</th>
<th>v(km/s)d</th>
<th>A_Hαe</th>
<th>M_B,Tf</th>
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<tbody>
<tr>
<td>M 51</td>
<td>Sbc-II</td>
<td>64°</td>
<td>8.4</td>
<td>464</td>
<td>0.07</td>
<td>-21.0</td>
</tr>
<tr>
<td>M 81</td>
<td>Sb-II</td>
<td>60°</td>
<td>3.6</td>
<td>-36</td>
<td>0.23</td>
<td>-20.8</td>
</tr>
<tr>
<td>M 101</td>
<td>ScdI</td>
<td>17°</td>
<td>7.4</td>
<td>251</td>
<td>0.07</td>
<td>-21.5</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>ScIII</td>
<td>62°</td>
<td>3.2</td>
<td>131</td>
<td>0.25</td>
<td>-19.2</td>
</tr>
<tr>
<td>NGC 4395</td>
<td>SdIII-IV</td>
<td>38°</td>
<td>2.6</td>
<td>317</td>
<td>0.07</td>
<td>-16.7</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>ScII</td>
<td>42°</td>
<td>5.9</td>
<td>48</td>
<td>1.43</td>
<td>-21.5</td>
</tr>
<tr>
<td>IC 342</td>
<td>Scd</td>
<td>20°</td>
<td>2.1</td>
<td>32</td>
<td>1.63</td>
<td>-20.2</td>
</tr>
</tbody>
</table>

a From the Revised Shapley-Ames Catalog (Sandage & Tammann 1987) except that IC 342 type is from Tully(1988).

b Inclination data are from Tully(1988) except the inclination for M 101 is from Zaritsky et al. (1990).


d Weighted mean observed heliocentric radial velocity from Revised Shapley-Ames Catalog (Sandage & Tammann 1987) except that v for IC 342 is from Tully(1988).

e Galactic extinction in magnitudes at Hα, estimated based on the foreground Galactic HI column density (Stark et al. 1992) in the direction of the objects. The conversion is done by assuming N_HI/E_B−V = 5×10^{21} cm^{-2} mag^{-1} and A_Hα = 2.5 E_B−V.

f Total absolute magnitude in the B band based on the apparent magnitude from the Revised Shapley-Ames Catalog (Sandage & Tammann 1987) (except that IC 342 M_B,T is from Tully(1988)), corrected to our adopted distance. These values have been corrected only for foreground Galactic extinction.
Table 2. DIM Hα Imaging Results

<table>
<thead>
<tr>
<th>Object</th>
<th>Hα Flux (^a) (erg s(^{-1}) cm(^{-2}))</th>
<th>(I_{Hα}) (^b) (L⊙)</th>
<th>(Σ_{60α}) (^c) (pc cm(^{-6}))</th>
<th>(Σ_{e}) (^d) (pc cm(^{-6}))</th>
<th>(r_e) (^e) (kpc)</th>
<th>(\frac{Σ_{e}}{\bar{Σ}_{Hα}}) (^f)</th>
<th>(a_{25}×b_{25}) (^g) (kpc)</th>
<th>(n) (^h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 51</td>
<td>(2.0\times10^{-11})</td>
<td>4.4\times10(^7)</td>
<td>130</td>
<td>120</td>
<td>4.2</td>
<td>0.35</td>
<td>27.4\times16.9</td>
<td>0.42</td>
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<tr>
<td>M 81</td>
<td>(3.7\times10^{-11})</td>
<td>1.5\times10(^7)</td>
<td>75</td>
<td>30</td>
<td>4.2</td>
<td>0.20</td>
<td>28.2\times14.8</td>
<td>1.1</td>
</tr>
<tr>
<td>M 101</td>
<td>(3.7\times10^{-11})</td>
<td>6.3\times10(^7)</td>
<td>105</td>
<td>35</td>
<td>10.2</td>
<td>0.13</td>
<td>62.0\times57.9</td>
<td>0.43</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>(4.4\times10^{-11})</td>
<td>1.4\times10(^7)</td>
<td>140</td>
<td>160</td>
<td>2.1</td>
<td>0.23</td>
<td>20.4\times11.5</td>
<td>0.43</td>
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<tr>
<td>NGC 4395</td>
<td>(9.2\times10^{-12})</td>
<td>1.9\times10(^6)</td>
<td>60</td>
<td>30</td>
<td>1.7</td>
<td>0.11</td>
<td>10.0\times8.3</td>
<td>1.1</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>(1.1\times10^{-10})</td>
<td>1.2\times10(^8)</td>
<td>280</td>
<td>280</td>
<td>4.5</td>
<td>0.40</td>
<td>19.7\times16.8</td>
<td>0.32</td>
</tr>
<tr>
<td>IC 342</td>
<td>(1.7\times10^{-10})</td>
<td>2.3\times10(^7)</td>
<td>160</td>
<td>110</td>
<td>2.9</td>
<td>0.31</td>
<td>13.1\times12.8</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Note. — Fluxes, luminosities and surface brightness have been corrected for foreground Galactic extinction based on the extinctions listed in Table 1.

\(^a\)Total Hα flux.

\(^b\)Total Hα luminosity.

\(^c\)Foreground extinction-corrected mean Hα surface brightness within the galaxy’s B = 25 mag arcsec\(^{-2}\) isophote (measured from foreground extinction-corrected limiting surface brightness of 30 pc cm\(^{-6}\) for NGC 6946 and IC 342 and from 15 pc cm\(^{-6}\) for the rest of galaxies) converted to emission measure assuming an electron temperature of \(10^4\) K (\(5\times10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) corresponds to 25 pc cm\(^{-6}\)).

\(^d\)Foreground extinction-corrected mean Hα surface brightness within Hα half light radius measured from \(-3\sigma\) of background and converted to emission measure.

\(^e\)Hα half light radius.

\(^f\)Ratio of the area above a common limiting surface brightness that is used to measure \(\bar{Σ}_{Hα}\) to the total physical area within the 25 B mag arcsec\(^{-2}\) isophote (\(A_{\text{true}} = \pi ab/4\)). This shows the fractional area used in our measurements of the images.

\(^g\)Major and minor axis diameter for the 25 B mag arcsec\(^{-2}\) isophote (adopted from RC3).

\(^h\)Power-law index of the distribution function for the DIM (\(\Sigma/\bar{Σ} \leq 1\)) defined as \(\frac{dA}{\Sigma_{Hα}} \propto \left(\frac{\Sigma}{\bar{Σ}}\right)^{-n}\). This index indicates the relative prominence of the DIM in different galaxies. A larger index means a more profuse DIM.
REFERENCES


Karachentsev, I. D. & Tikhonov, N. A. 1993, A&AS, 100, 227


McCall, M. L. 1982, dissertation, Univ. Texas at Austin


Rowan-Robinson, M. 1985, The Cosmological Distance Ladder (New York: Freeman)


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Fig. 1.— Continuum-subtracted Hα emission-line images in grayscale for a) M 51, b) M 81, c) M 101, d) NGC 2403, e) NGC 4395, f) NGC 6946, and g) IC 342. North is to the top and East is to the left. The straight lines mark the slit positions we used in the spectroscopic observations (WHL and Wang 1998). The scale of the images is represented by the length of the slit of 5′.

Fig. 2.— The growth curve of fractional Hα flux as a function of emission measure cutoff for our sample galaxies. Each plotted point corresponds to the relative flux contributed by pixels whose surface brightness lies between −3σ below the background up to the given surface brightness (emission measure). Symbols for different objects are explained on the figure.

Fig. 3.— The normalized number of pixels in the Hα image within a given surface brightness interval (d lg(Σ) = lg(1.25)) vs. the relative surface brightness (scaled by the mean surface brightness in the galaxy Σ̄). The surface brightness plotted starts at minimum values of 30 pc cm⁻⁶ for NGC 6946 and IC 342, and 15 pc cm⁻⁶ for the other galaxies, and it increases by a factor of 1.25 at each successive step. At each interval of surface brightness the number of pixels is counted and normalized by total number of pixels with surface brightnesses greater than the minimum values given above. The solid line is the model prediction for high surface brightness gas based on the typical luminosity function (N(L)∝ L⁻²) and exponential radial brightness profiles of HII regions. See the text for details.

Fig. 4.— The area used to measure the mean surface brightness Σ̄ (dark regions) compared to the total disk area for M 51 and M 101. The area and Σ̄ are used to scale the distribution function in Figure 3. a) M 51. The fraction of total disk area used is ∼35%. b) M 101. The fraction of total disk area used is ∼10%.
Fig. 5.— The growth of fractional Hα flux vs. the growth of the fractional covering area. The flux contributed, and the area occupied, are measured from the same minimum surface brightnesses as in Figure 3 up to a given relative surface brightness. The values of these relative surface brightnesses ($\Sigma/\bar{\Sigma}$) are marked by ticks increasing from 0.4 (lower-left corner) to 3 (upper-right corner) with a stepsize representing a factor of 1.25 increase in surface brightness. The area is normalized in the same way as in Fig. 3. See the text for details.