ON THE DYNAMICAL AND PHYSICAL STATE OF THE “DIFFUSE IONIZED MEDIUM” IN NEARBY SPIRAL GALAXIES

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ABSTRACT

We report the initial results from a program to study the morphology, physical state, and kinematics of the “diffuse ionized medium” (DIM) in a sample of the nearest and brightest late-type galaxies. For each of five galaxies (NGC 2403, M81, NGC 4395, M51, and M101), we have analyzed deep narrowband Hα images of the entire star-forming disk and long-slit spectra of the inner (∼10 kpc) disk with a resolution of 40−75 km s⁻¹. We find that the DIM covers most of the star-forming disk and is morphologically related to the presence of high surface brightness gas (the giant H II regions). The DIM and the giant H II regions differ systematically in their physical and dynamical state. The DIM is characterized by enhanced emission in the low-ionization forbidden lines ([O i], [N ii], and [S ii]), and even the high-ionization [O iii] λ5007 line is moderately strong in the DIM in at least three cases. This last result contrasts with upper limits on the [O iii] surface brightness in the local DIM of our own Galaxy (the “Reynolds Layer”). We directly verify the inference made by Lehnert and Heckman that the DIM contributes significantly to the spatially integrated (global) emission-line ratios measured in late-type galaxies. We also find that the DIM is more disturbed kinematically than the gas in the giant H II regions. The deconvolved (intrinsic) widths of the Hα and [N ii] λ6584 lines range from 30 to 100 km s⁻¹ (FWHM) in the DIM compared to 20−50 km s⁻¹ in the giant H II regions. The high-ionization gas in the DIM is more kinematically disturbed than the low-ionization gas: the [O iii] λ5007 lines have intrinsic widths of 70−150 km s⁻¹. The differing kinematics implies that the DIM is not a single monolithic phase of the ISM. Instead, it may consist of a “quiescent” DIM with a low ionization state and small scale height (few hundred parsec) and a “disturbed” DIM with a high ionization state and moderate scale height (0.5−1 kpc). We argue that the quiescent DIM is most likely photoionized by radiation from O stars leaking out of giant H II regions (although this requires fine-tuning the opacity of galactic disks to ionizing radiation). The disturbed DIM is most likely heated by the mechanical energy supplied by supernovae and stellar winds. Since the disturbed DIM accounts for only a minority (<20%) of the Hα emission in the regions we have studied, there is no fundamental energetics problem with this model, but it does require mechanically heated gas to have a high areal covering factor in the inner disk (which needs to be confirmed observationally). We find no clear discontinuity between the physical and dynamical properties of the giant H II regions and the quiescent DIM. The quiescent DIM is morphologically related to the giant H II regions and there is a smooth dependence of the emission-line ratios and emission-line widths on the surface brightness of the emission. Thus, we suggest that a unified approach to the study of the DIM and giant H II regions in star-forming galaxies will prove fruitful.

Subject headings: galaxies: ISM — galaxies: kinematics and dynamics — galaxies: spiral — H II regions

1. INTRODUCTION

The interstellar medium (ISM) in our Galaxy is known to be a multiphase complex system. The most recently discovered major component of the ISM is the widespread diffuse ionized medium (Reynolds 1990; Kulkarni & Heiles 1988). This gas, usually called the “Reynolds Layer,” is characterized by a relatively low ionization state compared to normal H II regions, a low surface brightness, relatively large scale height, and substantial energetic requirements. The latter are so severe that the Reynolds Layer must either soak 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 the Galactic disk and propagate to moderate scale heights. In either case, the implications for our understanding of the structure and energetics of the interstellar medium are considerable.

In several nearby normal spiral galaxies, gas with properties apparently similar to the Reynolds Layer has been found as well (see recent reviews by Dettmar 1992; Rand 1996a; Walterbos & Braun 1996). This gas has been variously referred to as the “diffuse ionized medium” (DIM), “diffuse ionized gas” (DIG), and “warm ionized medium” (WIM). In this paper we will adopt the acronym DIM. In the best studied case of the edge-on galaxy NGC 891 (Dettmar 1990; Rand, Kulkarni, & Hester 1990), a DIM in the form of filaments and bubbles can be detected out to more than a few kiloparsecs from the disk midplane (see also Rand 1997). A DIM with similar chaotic structure can

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be seen in some other face-on late-type galaxies such as M33 and M31 (see, e.g., Courtes et al. 1987; Walterbos & Braun 1994). This diffuse gas is (like the Reynolds Layer) characterized by the relative strength of low-ionization emission lines such as [O II] λ3727, [S II] λ6717, 6731, and [N II] λ6584 (see, e.g., Dettmar & Schulz 1992; Hunter & Gallagher 1997; Ferguson, Wyse, & Gallagher 1996a).

More generally, Lehner & Heckman (1994) have shown that the integrated optical spectra of a large sample of normal late-type galaxies published by Kennicutt (1992a, 1992b) provide very suggestive evidence that the DIM is generic to such galaxies: the global value of the [S II]/Hβ emission-line ratio is enhanced by an average factor of ~1.5–2.0 relative to the value characteristic of individual extragalactic H II regions. Based on the emission-line ratios in the DIM in the Milky Way and NGC 891, they estimated that the DIM would generically contribute at least 25% of the total Hβ emission in such galaxies. Indeed, direct Hβ imaging of several nearby star-forming galaxies has confirmed this estimate. The fraction of the DIM contribution is in the range of ~20%–40%, fairly independent of Hubble type (ranging from early-type spiral [Sb] to irregular) and galaxy inclination (Kennicutt et al. 1995; Ferguson et al. 1996a, 1996b; Hoopes, Walterbos, & Greenwalt 1996; Hunter & Gallagher 1997).

While the DIM is apparently ubiquitous, its dynamical state and its ionization and heating mechanism(s) are still poorly understood. To improve our understanding of the structure and evolution of the interstellar medium in our own and other galaxies, we need answers to questions such as how the DIM in external galaxies is energized and how much the DIM in the Milky Way shares in common with the extragalactic DIMs. Thus, we need to verify that DIMs are indeed generic in normal star-forming galaxies and to elucidate the properties of the DIM in such galaxies. We have therefore conducted an investigation of a carefully selected sample of the nearest, largest, and brightest normal late-type galaxies. We have selected our sample of galaxies according to the following criteria:

1. Late Hubble type (Sb or later). Such galaxies have relatively strong and easily studied optical line emission (typical global Hβ equivalent widths of 30–100 Å; see Kennicutt 1992a, 1992b). The integrated emission-line spectra of such galaxies contain a substantial contribution from low-ionization gas (Lehnert & Heckman 1994).

2. Nearby (distance < 10 Mpc). This allows us to obtain images with the highest possible spatial resolution (1" is typically 20–50 pc), which is crucial for detecting faint filamentary emission and determining its morphology and structure.

3. Large angular size (D25 ≥ 10''), so that we have the maximum number of resolution elements across the galaxy.

4. Inclination ≤ 65°. We exclude galaxies seen nearly edge-on where line-of-sight projection effects become severe.

In this paper, we report our first results for five galaxies in the sample: M51, M81, M101, NGC 2403, and NGC 4395. Some properties of these galaxies are summarized in Table 1. Our data consist of both narrowband Hβ images and long-slit spectroscopic observations. The spectra provide information on emission lines from Hβ, [S II] λ6717, 6731, and [N II] λ6584 in all five galaxies and on the Hβ, [O III] λ5007, and [O I] λ6300 lines in subsets of the sample. These data allow us to address the morphology and global energetics of the DIM, as well as its physical and dynamical state. Specifically, we focus on the measurements of the DIM contribution to the global Hβ luminosity, the physical state of the DIM (as probed via the relative strengths of the above emission lines), the dynamical state of the DIM, and the interrelationship between these physical and dynamical conditions.

### 2. OBSERVATIONS AND DATA REDUCTION

#### 2.1. Hβ Imaging Observations

Our imaging data were obtained during 1995 February 23–28 with the 0.9 m telescope at KPNO. We used a Tek 2048 × 2048 CCD with a 0.68 pixel size, which yielded a field of view of 23.2 × 23.2 arcmin². The Hβ filter had a FWHM of 26 Å and was centered on 6562 Å. Thus, relatively little flux from the [N II] λ6548, 6584 was included in these “on-band” images. “Off-band” observations of the continuum were made with a narrowband filter having a FWHM of 85 Å centered on 6568 Å. Several 1800 s (600 s)

| Object | Hubble Type | b (deg) | D' (Mpc) | v (km/s) | A_Hβ | M_B,T |
|--------|-------------|--------|---------|----------|------|-------|
| M51    | Sbc–II      | 64     | 8.4     | 464      | 0.06 | −21.0 |
| M81    | Sb–II       | 60     | 3.6     | −36      | 0.19 | −20.8 |
| M101   | ScdIII      | 17     | 7.4     | 251      | 0.06 | −21.5 |
| NGC 2403 | ScIII     | 62     | 3.2     | 131      | 0.21 | −19.2 |
| NGC 4395 | Scd–IV     | 38     | 2.6     | 317      | 0.06 | −16.7 |

* From Revised Shapley-Ames Catalog (Sandage & Tammann 1987).

† Inclination data are from Tully 1988 except the inclination for M101 is from Zaritsky, Elston, & Hill 1990.

‡ Distances are from Feldmeier, Ciardullo, & Jacoby 1997 (M51), Freedman et al. 1994 (M81), Kelson et al. 1996 (M101), Karachentsev & Makarov 1996 (NGC 2403), and Rowan-Robinson 1985 (NGC 4395).

§ Weighted mean observed heliocentric radial velocity from Revised Shapley-Ames Catalog (Sandage & Tammann 1987).

‖ Galactic extinction in magnitude at Hβ, estimated based on foreground Galactic H I column density (Stark et al. 1992) in the direction of the objects. The conversion is done by assuming N_H/σ_B = 5 × 10^{19} cm^{-2} mag^{-1} and A_Hβ = 2.1 E_B−V.

¶ Total absolute magnitude in B band from Revised Shapley-Ames Catalog (Sandage & Tammann 1987), adjusted to our adopted distance.
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 that have 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 the difference image agreed with the distribution of the Hα surface brightness in the long-slit spectra (see below) in the region of overlap.

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 them to those shown by the spectra (see § 2.2 for details of making the similar profile 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 H II regions in these galaxies (Kennicutt 1988) were used to flux calibrate our images. We have also used our long-slit spectra to check for consistency, and we find that the agreement in Hα flux in the regions of overlap is better than 10% for NGC 2403, NGC 4395, and M101 and 30% for M51. This suggests that our spectra of Hα were taken under nearly photometric conditions (see below).

Internal extinction in the galaxies has not been corrected for. Since the Galactic H I column density in the directions toward these galaxies is low, we did not correct the images for foreground Galactic extinction (listed in Table 1).

2.2. Optical Spectroscopic Observations

Our spectroscopic observations of these five galaxies were made using the Ritchey-Chrétien spectrograph on the 4 m telescope at Kitt Peak National Observatory during 1996 February 17–18, 1996 December 2–3, 1996 December 4–5, 1997 January 31–February 1, and 1997 February 3–4. The T2KB CCD was used as the detector, resulting in a scale of 0.69′′ per pixel. A 5′ long, 2′ wide slit was placed sampling the nuclei as well as representative spiral arm and interarm regions of our sample galaxies. The position angle of the slit for each galaxy is listed in Table 2 and shown in Figure 1. Based on Hα velocity maps, the slit orientation was chosen to be near the kinematic minor axes of each galaxy. This was done so that the velocity gradient of the emission-line gas along the slit should be minimized (allowing us to sum up the emission from large regions along the slit without introducing line broadening due to large-scale velocity shear). We also ensured that the amount of atmospheric differential refraction across the slit was insignificant for the particular slit position angles and hour angles of the observations.

Table 2 lists the spectrograph setup and relevant observation information. One set of data (hereafter the “red” spectra) covers the wavelength range from 6050 to 7090 Å centered at Hα. Because of vignetting in the spectrograph camera and focus variations across the detector, the useful spectral range is limited to the region from 6180 to 6950 Å. The data were obtained with the grating KPC-24 in second order. The resolution as determined from FWHMs of night-sky lines is ~0.8 Å (37 km s$^{-1}$) FWHM at Hα, which allows determination of deconvolved line widths as small as~20 km s$^{-1}$ in data with a high signal-to-noise ratio (7:1 or better). This can be compared with the minimum Hα FWHM resulting from pure thermal broadening of 22 km s$^{-1}$ for T = 10$^4$ K.

The second set of data (hereafter the “green” spectra) covers the useful wavelength range from ~4400 to 5300 Å and includes the Hβ and [O II] λ4959, 5007 lines. The spectral resolution as determined from FWHMs of strong emission lines in arc lamp spectra ranges from 1.0 to 1.5 Å FWHM (60–90 km s$^{-1}$). These data were obtained with either grating KPC-24 or grating KPC-18C in second order. The green spectrum of NGC 2403 was taken

| TABLE 2 | SPECTROSCOPIC OBSERVATIONS* |
|----------|-----------------------------|
| Object   | $\lambda$ Coverage* | Grating | Resolution | P.A. | Blocking Filter | Standard Star | Date |
|----------|-----------------------|---------|------------|------|-----------------|---------------|------|
| M51 ...... | 6560 6180–6950        | KPC-24  | 0.8–1.0    | 60   | GG495           | BD +26°2606   | 1996 Feb 17 |
| M81 ...... | 6560 4450–5250        | KPC-24  | 1.2–1.5    | 60   | BG39            | Feige 34      | 1996 Dec 4  |
| M101..... | 4800 6180–6950        | KPC-24  | 0.8–1.0    | 60   | GG495           | BD +26°2606   | 1996 Feb 17 |
| NGC 2403 .. | 6560 4500–5300       | KPC-24  | 1.0–1.2    | 140  | GG495           | BD +26°2606   | 1996 Feb 17 |
| NGC 4395 .. | 6560 6180–6950       | KPC-24  | 0.8–1.0    | 35   | GG495           | BD +26°2606   | 1996 Feb 17 |
|          | 4800 4360–5230       | KPC-18C | 1.0–1.2    | 35   | GG495           | BD +26°2606   | 1996 Feb 17 |

* All observations were made with the KPNO 4 m telescope using the Ritchey-Chrétien spectrograph and the T2KB CCD. A slit of 5′ long and 2′ wide is used centered on the nucleus of each of the objects.

b Useful spectral range estimated from 1500 pixels of the CCD.

c All gratings are set in second order.
FIG. 1a

FIG. 1b

Fig. 1.—Continuum-subtracted Hα emission-line images in gray scale for (a) M51, (b) M81, (c) M101, (d) NGC 2403, and (e) NGC 4395. North is to the top, and east is to the left. The slit position used for each galaxy is shown. The scale of the images is represented by the slit length of 5′.
twice on different nights, and the data were combined after proper reduction to achieve a high signal-to-noise ratio (S/N).

The data were reduced following standard procedures of biasing and flat fielding. Wavelength calibration was done with the package TWODSPEC.LONGSLIT in IRAF, using thorium-argon or helium-neon-argon arc lamp exposures. The uncertainty in wavelength after calibration for our high-resolution spectra was found to be less than 0.2 Å by comparing wavelengths of night-sky lines with standard values.

Since the galaxies have angular sizes that exceed the slit length, night-sky spectra were taken immediately before and after object exposures and were used to subtract the sky. To avoid introducing significant noise, we fitted the night-sky spectra in the spatial direction with a low-order (no higher than fourth) polynomial and used the fits (rather than the actual sky spectra) to do the sky subtraction. The relative strengths of night-sky lines varied during the observations in an unpredictable way. Thus, a straightforward method of subtracting a sky frame from an object frame may not remove some night-sky lines completely, especially near the Hα, [N II], and [O I] λ6300 lines in the red spectra. We instead adjusted the scaling factor for sky subtraction interactively in different wavelength ranges until a visually acceptable subtraction was done. As a result, slightly different scaling factors were used as necessary to subtract the sky in the red spectra near the Hα, [N II], [S II], and [O I] lines, respectively. In the green spectra, the problem was lessened as there are no strong night-sky lines near Hβ and [O III] λ5007. Only small residuals were left after sky subtraction, and they could be treated as additional background noise.

Spectra of the standard stars BD +26°2606, Feige 34, G191-B2B, and HZ 44 were taken to do spectrophotometric calibration. For the red spectra, the comparison between the spectra and our flux-calibrated Hα image (see § 2.1) suggests that the absolute fluxes of these spectra were very close to photometric values. We extrapolated the green spectra to the spectral region covered by our red spectra and found that both sets of spectra show consistent flux scales. This indicates that the green data were obtained under photometric conditions as well. Cosmic rays near important emission lines have been removed with the IRAF task IMEDIT before measurements.

We have then constructed the spatial profiles of the Hα surface brightness variation along the slit. To do so, the BACKGROUND task in IRAF was employed to fit (in the wavelength direction) the stellar continuum in the spectral region near Hα. To correct for the effect of the broad underlying stellar Hα absorption line, we used a fourth-order polynomial to model the absorption-line profile. Because the Hα emission line is almost always very narrow compared to the absorption feature, the emission line could be automatically rejected by the fitting program, and therefore only the absorption-line profile was fitted. The fits were subtracted from the original data to obtain the pure Hα emission-line fluxes. Although a polynomial is not an accurate representation of the real absorption line profile, this method has been very efficient and successful in removing most of the underlying absorption. The spatial profile of Hα surface brightness was then derived from the absorption-
corrected spectrum. The profile was used to locate the regions where the faint gas is and served as a reference for the continuum subtraction of our imaging data as well.

There has been no unique way to isolate the DIM from the rest of a galaxy. Here we simply set an upper limit of 5 × 10^{-17} \text{ergs s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2} to H\alpha surface brightness for the diffuse gas, which corresponds to an emission measure of 25 cm^{-6} pc at an electron temperature of 10^4 K. We used this limit to separate spectra of the diffuse gas from that of H\ II regions and obtained a set of apertures for spectra of the DIM. The red and green spectra were spa-
measured line emission of Hβ. Thus, the Hβ lines are generally registered using the positions of a few Hα regions along the slit. Therefore, the Hβ lines are usually very broad (FWHM > 20 Å) and shallow while the emission lines are usually very narrow (FWHM ≤ 2 Å), it is possible to correct for the absorption in a more rigorous manner than fitting the absorption features with a polynomial as discussed above. In most cases, the narrow Balmer emission lines appear on top of the broad valley of the absorption lines. It suffices to integrate the emission-line flux by simply setting the base of the Balmer emission lines as the continuum level. In rare cases in which the absorption features are only moderately broader than emission lines and further correction needs to be done, we compared the wings of the absorption features with those in typical A-type star spectra (Jacoby, Hunter, & Christian A). A good match allowed us to estimate how much emission is absorbed underlying the emission lines. Because of the spatially along the slit such that a S/N of at least 10:1 was achieved in the emission-line fluxes. The Hβ lines are relatively faint, so regions along the slit were summed to yield a minimum S/N for these measured fluxes of 5:1.

The IRAF task SPLOT was used to interactively measure integrated fluxes, centroids, and widths of the emission lines, assuming a single Gaussian for all the emission lines. The measured line widths were deconvolved using the instrumental resolution to give true widths. Since the instrumental resolution varied slowly as a function of wavelength and position along the slit, we were careful to use the local value of the instrumental resolution for this deconvolution (as determined from night-sky lines and the arc lamp exposures).

Since the absorption features of Hα and Hβ are usually very broad (FWHM > 20 Å) and shallow while the emission lines are usually very narrow (FWHM ≤ 2 Å), it is possible to correct for the absorption in a more rigorous manner than fitting the absorption features with a polynomial as discussed above. In most cases, the narrow Balmer emission lines appear on top of the broad valley of the absorption lines. It suffices to integrate the emission-line flux by simply setting the base of the Balmer emission lines as the continuum level. In rare cases in which the absorption features are only moderately broader than emission lines and further correction needs to be done, we compared the wings of the absorption features with those in typical A-type star spectra (Jacoby, Hunter, & Christian A). A good match allowed us to estimate how much emission is absorbed underlying the emission lines. Because of the narrow Balmer line widths of the DIM, there is negligible flux missed in the direct measurement of these emission lines with SPLOT.

For measurements of the Hα, [N II] λ6583, and [S II] λλ6717, 6731 emission-line fluxes in the DIM, we summed spatially along the slit such that a S/N of at least 10:1 was achieved in the emission-line fluxes. The Hβ and [O III] λ5007 lines are relatively faint, so regions along the slit were summed to yield a minimum S/N for these measured fluxes of 5:1.

We also measured the spectra of H II regions in the off-nuclear areas, defined to have Hα surface brightness above 2 × 10⁻¹⁶ ergs s⁻¹ cm⁻² arcsec⁻² (emission measure above 100 cm⁻⁶ pc). In this way we have sampled the brightest H II regions in our spectra, which can serve as a contrast to...
the diffuse gas. The M81 spectra do not cover this type of bright H II regions and were not measured this way. In addition, individual H II regions that appeared to be relatively isolated (not blended with other H II regions) were selected in order to study radial variations of the emission-line ratios [N II] \( \lambda 6583/\lambda 6548 \) and [S II] \( \lambda 6717, \lambda 6731/\lambda 6548 \) from the H II region out into the surrounding DIM. To do so, the spectra were extracted with 2\( ^\prime \)-4\( ^\prime \) long apertures marching outward from each H II region. The size of the aperture was chosen so that the signal-to-noise ratios of measured emission-line fluxes were at least 5:1.

The precise specifications of the spectroscopic apertures used and the resulting measurements of line ratios, line widths, and surface brightnesses for the DIM and H II regions are given in Tables 3 and 4 for the red and green spectra, respectively.

3. RESULTS

3.1. H\( \alpha \) Images

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\( ^\prime \) \times \( 2^\prime \). 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 in § 3.2, the wide distribution of the DIM has also been confirmed by our spectra, which have a higher sensitivity. The diffuse gas is preferentially along the edges of spiral arms and around isolated H II regions, as is generally the case for the DIM (see, e.g., Ferguson et al. 1996b; Hoopes et al. 1996). For M81, the bright diffuse gas component within a radius of 2\( ^\prime \)-3\( ^\prime \) 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).

To study the DIM contribution to the total H\( \alpha \) flux in our sample, we clipped out discrete H II regions at a given surface brightness level from the unsmeared images and smoothed the images with a 2\( ^\prime \) \times 2\( ^\prime \) box. Because the average surface brightness of the DIM (\( \sim \)10 pc cm\(^{-6} \)) is comparable to the noise of the background of the resulting clipped images, we determined the flux from these images by integrating from \(-3 \sigma \) of the background of the images to the clipping surface brightness level. We repeated this process over a range in the clipping threshold in surface brightness (emission measure). Figure 2 shows the fraction of total H\( \alpha \) flux the gas contributes as a function of emission measure cutoff. Figure 2 serves as only a rough estimate of the DIM contribution. The measurement was not made below a surface brightness corresponding to \( 3 \sigma \) above the background of the unsmeared images. This minimum clipping surface brightness level corresponds to an emission measure of 90 pc cm\(^{-6} \) for M51 and M101, 40 pc cm\(^{-6} \) for M81 and NGC 2403, and 60 pc cm\(^{-6} \) for NGC 4395. The depths of the images do not significantly affect the overall result in Figure 2.

There are four effects that should be noted when interpreting Figure 2. First, the light from H II regions, scattered by the optics in the telescope and camera and by the dust in the galaxies, has not been corrected. Hoopes et al. (1996) showed that this correction is minor for their sample galaxies. Furthermore, the emission-line ratios of the DIM (see § 3.2) are significantly different from those of typical H II regions. No scattering processes can account for this difference. Thus, scattered light is unlikely dominant in the DIM flux, and we do not consider this effect here. Second, a more reliable determination of this contribution should include a correction of the missed diffuse gas flux on top of clipped-out H II 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; see, e.g., Ferguson et al. 1996b; Hoopes et al. 1996) may increase the DIM fraction significantly, especially for low cutoff 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 our comparison of our spectra and images, this uncertainty is minor at the relevant levels of emission measure and will not alter the essential behavior of the growth curve. Fourth, no extinction correction has been applied. In a situation in which H II regions suffer more average extinction than the DIM, the intrinsic DIM fraction should drop accordingly.

The growth curves shown in Figure 2 vary among our sample galaxies. M51, M101, and NGC 2403 have an abundance of very bright H II regions in their disks. In these three galaxies, the DIM contributes to the global H\( \alpha \) luminosity at a relatively low level. NGC 4395 and M81 have a smaller number of bright H II regions, and so the DIM becomes more important globally. We verified that the high DIM fraction in M81 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 M81 is a quiescent, early-type spiral.
We have compared the growth curves of the three galaxies in the Sculptor group shown by Hoopes et al. (1996) with ours. NGC 300 has a growth curve very similar to NGC 4395 and M81, while NGC 253 and NGC 55 match our sample galaxies M51, M101, and NGC 2403 well. The variation of the growth curves among galaxies is then not primarily due to inclination. For example, M101 and NGC 253 have inclination angles of 17° and 78°, respectively, yet both galaxies show similar growth curves. The contribution of the DIM to the total Hα luminosity is probably a function of global star formation strength too. Obviously, the galaxies abundant in luminous giant H II regions tend to have a smaller fractional contribution to Hα luminosity from the DIM.

Although we (and others) have defined the DIM in terms of a surface brightness criterion, the D in DIM stands for “diffuse.” Thus, we have also 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. While some rigorous approach based on a Fourier analysis of the images could be attempted, we have characterized the “DIMness” of the galaxy by simply taking the ratio of the mean and the rms of the Hα surface brightness within the surface area of the galaxy delimited by the 25 B mag per square arcsec isophote. These results (and all the global properties of the Hα images we have measured) are listed in Table 5. Using the ratio of the mean/rms as a measure of DIMness, we find that M101 stands out from the rest of the sample. It is dominated by very bright giant H II regions that occupy only a small fraction of the disk surface area and has a correspondingly small ratios of mean/rms.

Interestingly, M51 has a pronounced “diffuse” Hα emission based on its high value of mean/rms. This morphological criterion thus yields a result that contrasts sharply with the “growth curve” shown in Figure 2. That is, M51 has a very small contribution from gas with low surface brightness (Fig. 2), but its emission is relatively diffuse (Table 5). It remains to be seen whether the absolute surface brightness or the morphology is the more fundamental and physically meaningful way of defining the DIM.

3.2. Spectroscopic Data
3.2.1. Overview of Properties of the DIM

Because of the better sensitivity of the spectral data compared to the images, the spectra can provide us with detailed information about the global distribution of the very faint DIM. One of the most interesting results from our spectroscopic data is that we can see truly diffuse, low surface brightness emission-line gas almost everywhere along the slit.

This is illustrated in Figure 3 (Plates 1–2), which shows the sections of the long-slit spectra containing emission lines of interest, and in Figure 4, which plots the surface brightness distributions of Hα, [N II], Hβ, and [O III] along the slit for galaxies for which we have data of sufficient quality. Hα + [N II] can be easily seen almost everywhere along the slit except for the [N II] emission in the NGC 4395 spectrum. Thus, we also include in Figure 3 the [S II] emission for NGC 4395, which shows detectable emission everywhere. The relative weakness of the [N II] emission throughout NGC 4395 is most likely an abundance effect (as we will discuss below).

Reliable detections of the [O III] λ5007 and Hβ lines were made in the DIM in all cases except for M81 (where the stellar background is very bright). The [O I] λ6300 line was reliably detected only in the DIM of NGC 2403 (Fig. 3). A noticeable feature in the green spectra of these galaxies is that [O III] λ5007 for the diffuse gas can sometimes be stronger than Hβ in the same spatial regions (the opposite of the usual case in the H II regions). We will discuss this in detail below.

As can be seen in Figure 4, faint gas can be clearly seen below our arbitrary Hα surface brightness limit for the DIM (< 5 × 10^{-17} ergs s^{-1} cm^{-2} arcsec^{-2}). We reject the possibility that the diffuse emission is mainly from the light of H II regions scattered into the line of sight because this is inconsistent with the pronounced differences in the emission-line ratios between the DIM and the H II regions (as we will show in the following section). Thus, our spectroscopic data shows that the DIM is apparently ubiquitous throughout the inner disks of late-type galaxies.

To verify the suggestion made by Lehnert & Heckman (1994) that the DIM significantly contributes to the integrated spectra of normal star-forming galaxies, we measured the [N II]/Hα, [S II]/Hα, and [O III]/Hβ ratios from the integrated spectra. In these we excluded the nuclear contribution from within the central ~25" aperture because the slit length is only 5" (so our original spectra may be biased toward the nuclear spectra, which may not be representative of the galaxy disk). We then find that for each galaxy, the [N II]/Hα and [S II]/Hα ratios from the integrated spectrum are enhanced relative to the corresponding

| Table 5 |
| DIM Imaging Results* |
| Object | Hα Flux (ergs s^{-1} cm^{-2}) | \( L_{Hα} \) (\( L_\odot \)) | Mean \( \Sigma_{Hα} \) (pc cm^{-2}) | Mean/rms | \( \Sigma_{50} \) |
| M51 | 2.0 × 10^{-11} | 4.4 × 10^{7} | 35 | 0.24 | 400 |
| M81 | 3.2 × 10^{-11} | 1.3 × 10^{7} | 16 | 0.30 | 74 |
| M101 | 3.7 × 10^{-11} | 6.3 × 10^{7} | 9.5 | 0.12 | 230 |
| NGC 2403 | 3.3 × 10^{-11} | 1.1 × 10^{7} | 19 | 0.19 | 230 |
| NGC 4395 | 9.2 × 10^{-12} | 1.9 × 10^{6} | 9.2 | 0.24 | 74 |

* Correction for foreground Galactic extinction has not been applied to the data in this table.

\( \Sigma_{Hα} \) surface brightness within the galaxy’s B = 25 mag arcsec^{-2} isophote converted to emission measure assuming an electron temperature of 10^4 K (5 × 10^{-17} ergs s^{-1} cm^{-2} arcsec^{-2} corresponds to 25 pc cm^{-3}).

\( \Sigma_{50} \) The ratio of mean to rms of Hα surface brightness. This ratio is used to characterize the “DIMness” of a galaxy. See text for more details.

Hα surface brightness level at which fainter gas contributes 50% of total Hα flux. The unit is converted to that of emission measure assuming an electron temperature of 10^4 K.
H II region values in the same region of these galaxies by a factor from 1.1 to 2, while the [O III]/Hβ ratio shows a range of behavior but no systematic trend (Table 6). This is quantitatively consistent with the results of Lehnert & Heckman (1994) based on the analysis of the Kennicutt (1992a, 1992b) sample.

### 3.2.2. Line Ratios of DIM

Figure 5 shows representative spectra of the DIM in our sample galaxies near the Hα, [N II] λ6583, and [S II] λ6717, 6731. (b) Representative [O III] λ5007 line profiles compared with [N II] λ6583 line widths (illustrated as horizontal bars) that have been convolved to have the same instrumental resolution as the [O III] data. The [N II] λ6583 lines were measured from the same spatial regions where we measured the [O III] lines.
plotted the ratio of the [S II]/Hα lines versus the ratio of the [N II]/Hα for the DIM and H II regions. These line ratios are typically enhanced by about a factor of 3 in the DIM compared to the H II regions (see Table 6).

Note that while there is a strong correlation between [N II]/Hα and [S II]/Hα in our sample, the [N II]/Hα ratios in NGC 2403 and NGC 4395 are systematically low compared to the other sample galaxies. This is most likely due to a lower N/S abundance ratio in the two former galaxies. As shown by Vila-Costas & Edmunds (1993), the origin of nitrogen has both a primary component and a secondary one, which implies that the nitrogen abundance scales linearly with metallicity at low metallicity but quadratically at medium and high metallicity. This means that the nitrogen abundance is more sensitive to metallicity variations compared to other heavy elements, such as sulfur, and that the N/O and N/S ratios decrease with decreasing metallicity.

### Table 6: Observed Typical Emission Line Ratios of the DIM

| Object     | [N II] λ6583/Hα | [S II] λ6717/Hα | [O I] λ6300/Hα | [O III] λ5007/Hα |
|------------|-----------------|-----------------|----------------|-----------------|
| M51        | 1.2; 0.44       | 0.47; 0.11      | 0.1*; 0.015    | 1; 0.4          |
| M81        | 1.6; 0.53       | 1.1; 0.43       | ...            | ...             |
| M101       | 0.64; 0.26      | 0.36; 0.13      | ...            | ...             |
| NGC 2403   | 0.29; 0.28      | 0.45; 0.21      | 0.2; 0.030     | 1.0; 0.4        |
| NGC 4395   | 0.19; 0.11      | 0.42; 0.14      | ...            | 0.6; 2          |
| Galaxy     | 0.3; ...        | 0.35; ...       | <0.02; ...     | <0.2; ...       |
| NGC 891 reg. 1 | 0.6–1.1; ... | 0.3–0.6; ... | <0.05; ... | <0.4; ... |

**Note.**—Listed line ratios are from averaged DIM and H II region spectra. Semicolons separate values for the DIM and H II regions, respectively; for the Galaxy and NGC 891, only the DIM line ratios are given.

* [S II] λ6731 is not included in order to compare to the data of the Milky Way and NGC 891. Including this line would increase the ratios by a factor of 1.7.

* Ratios marked with an asterisk are calculated from the marginally detected [O I] λ6300 line flux.

* From Reynolds 1990, 1991.

* From Dettmar 1992.

Given the correlation between metallicity and absolute magnitude in late-type galaxies (see, e.g., Zaritsky, Kennicutt, & Huchra 1994; Skillman, Kennicutt, & Hodge 1989), it is natural that NGC 4395 and NGC 2403 would have the lowest metallicities in our sample (see Table 1). In fact, measurements of the O/H and N/O abundances in the bright H II regions in the inner parts of these galaxies (Villa-Costas & Edmunds 1993) support this idea: the N/O ratios range from roughly twice solar (M51), to roughly solar (M81 and M101), to 40% solar (NGC 2403 and NGC 4395).

In our initial analysis, we have selected the extremes in surface brightness in the ionized gas (the DIM and the giant H II regions). To explore the behavior of the [N II] and [S II] lines further, we have then measured the relative strengths of these lines as a function of radius from the center of several giant H II regions in each galaxy. These H II regions do not cover any bright H II regions, so we only include measurements for the faint H II regions. **Right-hand panel:** Same as left-hand panel except that the data points are grouped by Hz surface brightness (SB) as follows: SB below 5 × 10^{-17} ergs s^{-1} cm^{-2} arcsec^{-2} (open squares), which is the cutoff surface brightness we adopted to isolate the DIM; SB above 2 × 10^{-16} ergs s^{-1} cm^{-2} arcsec^{-2} (filled squares), which is the lower limit we used to select bright H II regions; and SB below 2 × 10^{-16} ergs s^{-1} cm^{-2} arcsec^{-2} but above 5 × 10^{-17} ergs s^{-1} cm^{-2} arcsec^{-2} (boxed crosses).
regions were selected to be bright and spatially isolated from other H II regions to allow us to track the transition from giant H II region into the surrounding DIM. The positions of the selected H II regions relative to the nuclei are 100° northeast and 113° southwest for M51, 117° southeast and 82° southeast for M101, 66° southwest for NGC 2403, and 37° northeast for NGC 4395. The results are shown in Figure 7, where we can see that there is generally a smooth and monotonic increase in the [S II]/Hz and [N II]/Hz ratios with increasing distance from the core of the H II region. This result emphasizes the continuity in properties between the high and low surface brightness gas.

This continuity can be seen explicitly in Figure 8, which plots the dependence of the [S II]/Hz ratio as a function of Hz surface brightness. This plot contains all the regions that we have measured (the H II regions, the DIM, and the transition regions of intermediate surface brightness around the isolated H II regions). The plot shows that the [S II]/Hz ratio is strongly and inversely correlated with surface brightness over more than 2 orders of magnitude in surface brightness, for all five galaxies. The [N II]/Hz ratio exhibits a similar behavior, but the galaxy-to-galaxy scatter is larger, presumably because of the variation in the N/O abundance ratio among the galaxies (as discussed above).

The [O I] 6300 line—which is a tracer of warm neutral gas and a unique probe of the DIM—is difficult to detect in our spectra. The [O I] line in M81 is coincident with the strong telluric [O I] line, while the [O I] line in NGC 4395 is coincident with another sky line at ~6306.9 Å. Therefore, no useful measurements in these two galaxies were possible. In the other galaxies we have summed all the DIM data into a single spectrum per galaxy. We then have made marginal (5σ) detections in M101 and M51 and a firm detection in NGC 2403. In these three cases, the relative intensity of the [O I] line is 0.1–0.2 of Hz (Table 6). These ratios are ~1 order of magnitude larger than in the corresponding H II regions ([O I] 6300/Hz ≈ 0.01–0.03).

While the enhanced strengths of the low-ionization lines due to [O I], [S II], and [N II] are not surprising in the DIM, our data imply that the relative strength of the high-ionization [O III] λ5007 line is enhanced in the DIM relative to the giant H II regions in most of our sample galaxies. This can be seen in Table 6 and Figure 9. This result is quite surprising if the DIM is simply photoionized by a dilute radiation field due to the same population of stars that excite the giant H II regions (the “leaky H II region” model). In this case, the enhanced low-ionization lines in the DIM would be attributed to a lower ionization parameter U (the ratio of ionizing photons to electrons) in the DIM compared to that in the H II regions (see Domgø and Mathis 1994). The simplest version of these models would therefore
FIG. 9.—Line ratio diagrams. Solid squares represent bright H II region data from M51, M101, NGC 2403, and NGC 4395; the DIM data points are represented in the same convention adopted in the previous figures for M101 (asterisks), M51 (triangles), NGC 4395 (large crosses), and NGC 2403 (open circles). Arrows mean that [O III] λ5007 is below our 5σ detection limit. The standard photoionization model (solid curve) and dust depletion model (dotted curve) of J. Sokolowski (1993, private communication) are also shown. Small crosses on the curves indicate the value of the ionization parameter $U$ (from lower-right to upper-left along each curve): $3 \times 10^{-4}$ to $6 \times 10^{-3}$. The high [O III]/Hβ point for NGC 4395 is for gas near the Seyfert nucleus.

require that the [O III]/Hβ ratio should drop as we move from the giant H II regions into the DIM. Unfortunately, since the [O III] surface brightness is too low in our data, we cannot directly test this prediction by plotting the radial variation of the [O III]/Hβ line ratio across individual H II regions (as we do for other lines in Fig. 7).

3.2.3. Kinematics

While there have been many recent studies of emission-line ratios in the DIM, these studies have generally had spectral resolution that was too low to probe the kinematics of the DIM. In contrast, our spectra are able to resolve the emission-line widths throughout the DIM and in most of the giant H II regions. This has led to several surprising and illuminating results.

We begin with a discussion of our results for the Hα and [N II] λ6584 lines, since these are the two brightest lines in the DIM and since our red spectra had better velocity resolution than the green data (instrumental FWHM of typically 40 and 75 km s$^{-1}$, respectively). From Figure 10 we see that there is an overall weak trend for the deconvolved (intrinsic) emission-line widths of these two lines to inversely correlate with the Hα surface brightness. Typical Hα and [N II] emission-line widths range from 30 to 100 km s$^{-1}$ FWHM in the DIM, compared to typically 20–50 km s$^{-1}$ in the giant H II regions (recall that pure thermal Doppler broadening at $T = 10^4$ K produces a FWHM of $\sim 22$ km s$^{-1}$ for hydrogen). We conclude that the low-ionization gas in DIM is less quiescent than in the H II regions, but the velocity dispersions are still small compared to theoretical expectations for gas that has been shock-heated and pushed to large scale heights out of the disk (as we discuss in detail in § 4).

Given the strong correlation we find between the [S II]/Hα line ratio and Hα surface brightness (Fig. 8), it is not surprising that there is a trend for the [S II]/Hα ratio to be positively correlated with the Hα and [N II] emission-line widths (Fig. 11). The trend is the same for the [N II]/Hα ratio but with more scatter (again, presumably reflecting galaxy-to-galaxy variations in the N/O abundance ratio). This correlation between the physical state of the gas (line ratios) and the dynamical state of the gas (line widths) suggests that mechanical heating may play some role in exciting the low-ionization lines in the DIM. However, the best
The correlation of line ratio is with surface brightness (compare Figs. 8 and 11).

We now turn our attention to the [O \textsc{iii}] λ5007 emission-line kinematics. This line is very faint in the DIM, and we have had to sum up large regions of DIM to attain a high enough signal-to-noise ratio to make measurements of the line widths (see Table 4). Nevertheless, we find that not only can we spectroscopically resolve the [O \textsc{iii}] line profiles, but that the deconvolved line widths are significantly larger than the Hα and [N \textsc{ii}] lines in the same region of the DIM (Fig. 5). This can be quantitatively evaluated in (Fig. 12). The deconvolved FWHM of the [O \textsc{iii}] λ5007 line vs. the deconvolved FWHM of the [N \textsc{ii}] λ6583 line for regions in the DIM. The solid line is the locus where FWHM([N \textsc{ii}] λ6583) = FWHM([O \textsc{iii}] λ5007). The data point notation is the same as in the previous figures. The arrows imply the [O \textsc{iii}] line width cannot be determined reliably based on our estimated minimum resolvable line width of 40 km s\(^{-1}\) for the [O \textsc{iii}] line.

Even if the gas in the quiescent DIM has a very low ionization state and therefore produces only a negligible amount of [O \textsc{iii}] λ5007 emission, the gas in the disturbed DIM must still produce a non-negligible amount of Hα emission. That is, for any plausible model for the heating of this gas, the Hα emission in the disturbed DIM will be at least 30% as strong as [O \textsc{iii}] λ5007 (see § 4.1 below). We measure the Hα line to be typically ~3 times brighter than the [O \textsc{iii}] line in the DIM (Table 6). Thus, the disturbed component of the DIM ought to contribute at least 10% to the total Hα emission in the DIM. We have therefore reanalyzed our data to see whether the Hα emission-line profile shapes in the DIM can be understood in terms of a strong narrow component (contributed by the quiescent DIM) and a weak broader component (contributed by the disturbed DIM). The modest signal-to-noise ratio in our data allows us only to say that any broad component can contribute no more than ~20% to the total Hα line flux, which is consistent with an expected minimum value of 10%.

4. DISCUSSION

4.1. The Energy Source for the DIM

4.1.1. Photoionization

The results in § 3.2.3 suggest that there may be more than one energy source for the DIM. For the quiescent DIM, the
leaky H II region model is appealing on a number of grounds. First, radiation from massive stars is the most abundant ionization source in these star-forming galaxies (by ~1 order of magnitude). Second, there is a morphological correspondence between the DIM and giant H II regions (Hoopes et al. 1996; Ferguson et al. 1996b; § 3.1 above). Third, we have emphasized the continuity in the physical and dynamical properties of the gas in the quiescent DIM and the H II regions (rather than the existence of any well-defined dichotomy). Fourth, the quiescent state of this component of the DIM argues against mechanical heating as the dominant ionization source. Finally, even simple models of photoionization by dilute stellar radiation can readily match the relative intensities of the low-ionization species in the quiescent DIM (as we now show).

The ionization state of photoionized gas is primarily determined by the ionization parameter \( U \), defined as the ratio of the density of ionizing photons and electrons in the gas. The low ionization state of the quiescent DIM (and the implied low value for \( U \)) is a natural consequence of the leaky H II region model. Averaged over the region interior to \( R_5 \), the mean Hz surface brightness of the disks of our galaxies (including both the DIM and the H II regions) is \( \sim 3 \times 10^{-17} \) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\). This corresponds to a disk-averaged flux of ionizing photons of \( \sim 10^6 \) s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\). If we assume that a fraction, \( f_{\text{DIM}} \), of these reach the DIM, then we find \( U = 2\pi \times 10^6 f_{\text{DIM}}/n_e c \) as the characteristic value of \( U \).

We can evaluate \( n_e \) by taking a temperature appropriate for photoionized gas (\( T \sim 10^4 \) K) and assuming the DIM is in pressure-balance with the rest of the ISM. In the solar neighborhood, \( P/k \sim 10^4 \) cm\(^{-3}\) K. The surface-mass density of stars in the inner disks of our galaxies is ~1 order of magnitude higher than the value in the solar neighborhood, while the surface-mass density of the interstellar gas is roughly similar to the local value. Provided that the scale height of this gas is not much less than the scale height of the stars, simple considerations of hydrostatic equilibrium then imply that the midplane pressures in the ISM in the inner disks of our galaxies will be of order \( P/k \sim 10^5 \) cm\(^{-3}\) K. Since these higher pressures are not directly demonstrated observationally, we will use \( P/k \sim 10^4 \) cm\(^{-3}\) K. We then obtain \( U = 4 \times 10^{-4} \) to \( 4 \times 10^{-5} f_{\text{DIM}} \) as the characteristic value in the midplane. These midplane values are appropriate for the quiescent DIM, since (as we will show in § 4.2 below) it must have a relatively small scale height.

Note that the actual value of \( U \) in the DIM will be larger than the above, since the DIM is spatially correlated with H II regions and therefore probably sees a photoionizing flux that is higher than the disk average. On the other hand, \( f_{\text{DIM}} \) is of order 10\(^{-1}\). The implied range in \( U \) is then consistent with photoionization models that show that the key diagnostic line ratios \( [\text{N II}] / \text{Hz} \) and \( [\text{S II}] / \text{Hz} \) peak for values of \( U \) in the range \( 3 \times 10^{-5} \) to \( 3 \times 10^{-4} \) (e.g., Sokolowski 1993, private communication).

This analysis also reveals why the leaky H II region model would have difficulties explaining the disturbed DIM. The lack of obvious broad wings on the Hz or \([\text{N II}]\) emission lines (§ 3.2) implies that the disturbed DIM must have a relatively high ionization state. Photoionization models show that very strong \([\text{O III}] \lambda 5007\) emission (e.g., \([\text{O III}] / \text{Hz} \beta \approx 1\)) requires \( \log U \approx -2 \). Using the same arguments as in the previous paragraph, values this large for \( U \) would require \( n_e < 0.02 f_{\text{DIM}} \) or \( P/k < 4 \times 10^2 f_{\text{DIM}} \) cm\(^{-3}\) K. This pressure is far below plausible ISM pressures. While the hydrostatic equilibrium condition implies that the gas pressure will drop with distance out of the disk plane, the required pressures are so low that the disturbed DIM would have to be located more than 6 pressure scale heights above the inner disk (which is inconsistent with our estimates in § 4.2 below).

Perhaps the biggest challenge for photoionization models is explaining the perservativeness of the DIM. Our long-slit data showing Hz, \([\text{N II}]\), and \([\text{S II}]\) emission throughout the inner disk only exacerbates this problem. Here we would like to emphasize the curious fact that the opacity of the ISM to ionizing radiation in these galaxies seems to be “fine-tuned.” That is, we can imagine two extremes for the fate of ionizing radiation produced by massive stars. First, it may all be absorbed locally around the complexes of O stars so that a deep Hz image would reveal small intense “islands” of high surface brightness surrounded by very dark “oceans” that cover most of the disk. This is manifestly not the case (see Figs. 1 and 2). The other extreme case is one in which the ISM is optically thin to ionizing radiation, allowing it to freely escape into the galactic halo or intergalactic space. This also seems far from reality (Leitherer et al. 1995; Giallongo, Fontana, & Madau 1997). Instead, the ISM seems to be arranged such that it is optically thin enough to allow the gas throughout a significant fraction of the ISM to be bathed in the diffuse radiation of the hot stars, yet optically thick enough to capture the great majority of the ionizing radiation. Why is this so? Is this the result of some subtle feedback loop between star formation and the structure and physical state of the ISM?

4.1.2. Mechanical Heating

While we cannot totally rule out photoionization for the disturbed DIM, we are lead to consider a totally different ionization source. The disturbed kinematics of this gas could implicate mechanical heating of the ISM by supernovae and stellar winds. We therefore consider two alternative forms for such mechanical heating: radiative shocks and turbulent mixing layers.

Models of low-density radiative shocks (Shull & McKee 1979; J. C. Raymond 1997, private communication) show that suitably strong \([\text{O III}] \lambda 5007\) emission (e.g., \([\text{O III}] / \text{Hz} = 1–3\) ) is attained for shock speeds \( > 100 \) km s\(^{-1}\). A strong shock will accelerate the shocked material to three-fourths of the shock velocity, so we would expect the velocity dispersion in the DIM to be \( > 75 \) km s\(^{-1}\). The typical measured line widths for the \([\text{O III}] \lambda 5007\) line imply a three-dimensional velocity dispersion for the disturbed DIM of 60–100 km s\(^{-1}\), so the required shock speeds are plausible.

Turbulent mixing layers (Slavin, Shull, & Begelman 1993) are the interface between hot gas flowing past cold clouds and hence have a temperature that is intermediate between the cold and hot phases. The models yield values of \([\text{O III}] \lambda 5007 / \text{Hz} \approx 1.5–3\) for much of the parameter space these authors explored. This specific range encompasses mixing layers with log \( T \approx 5.3 \) and 5.5 when the “cold” clouds have log \( T = 4\) and mixing layers with log \( T = 5.5\) when the cold clouds have log \( T = 2\). Cooler mixing layers do not produce significant \([\text{O III}]\) emission. The turbulent mixing layer models have one advantage over the shock models in that they do not demand that the mixing layer necessarily have a large velocity dispersion. Satisfactorily strong \([\text{O III}]\)
emission relative to Hα can be produced when the hot gas moves past the cold cloud at either 25 or 100 km s⁻¹ (consistent with the observed [O III] line widths in the DIM). High relative velocities do lead to enhanced emissivity at a given gas pressure, however (see below).

A potential problem with both the shock- and turbulent-mixing layers models (especially the latter) is the low predicted [O III] λ5007 surface brightness for gas having the modest pressures appropriate to a normal disk galaxy ISM (P/k ~ 10⁴ K cm⁻³ to ~ 10⁶ K cm⁻³ in the inner disk regions probed by our spectra). For P/k = 10⁵ K cm⁻³, the predicted [O III] λ5007 surface brightnesses from shocks with v ~ 100–150 km s⁻¹ are in the range 3 × 10⁻¹⁸ to 7 × 10⁻¹⁸ ergs cm⁻² s⁻¹ arcsec⁻². This is similar to typical [O III] λ5007 surface brightnesses in the DIM of ~ 5 × 10⁻¹⁸ to 1 × 10⁻¹⁷ ergs cm⁻² s⁻¹ arcsec⁻² at best, even for P/k = 10⁵ K cm⁻³. This is 1 order of magnitude smaller than the typical observed values in the DIM and would require the presence of many (>10) turbulent mixing layers along a typical line of sight through the galaxy disk.

As noted in § 1, energizing the entire DIM seems problematic using only the mechanical energy from supernovae and stellar winds, since it requires tapping essentially all of this mechanical energy. However, the energetic requirements for ionizing the disturbed DIM alone are substantially less. That is, the disturbed DIM contributes less than 20% to the total Hα luminosity of the DIM (§ 3.2.2), at least in the regions probed by our spectra. Thus, mechanical heating cannot be ruled out on simple energetic grounds.

We have seen that the DIM is very pervasive in the inner disks of our galaxies, so mechanical heating of the DIM would require that nearly every line of sight through the disk intersect regions of mechanically heated gas. It is not clear whether the topology or “porosity” (McKee & Ostriker 1977) of the ISM in typical disk galaxies is consistent with this requirement. Observationally, there is no direct evidence for a high covering fraction of diffuse gas mechanically heated to a temperature of 10⁵ K or more in typical galactic disks. For example, Heiles (1990) and Oey & Clarke (1997) have concluded that only a small fraction of the surface area of the disks of the Milky Way, M31, and M33 is covered by the hot superbubbles created by supernovae and stellar winds. On the other hand, the available information about soft X-ray emission from the nearby spiral galaxies suggests the existence of diffuse, relatively hot gas (T ≥ 10⁶ K), but little is known about the corresponding areal covering factor. Perhaps the best studied case of diffuse, soft X-ray emitting gas in our sample galaxies is M101. Snowden & Pietsch (1995) have shown that in the inner disk of M101, the gas has T ~ 10⁵.8 K and a covering fraction of order unity. To heat up the gas to this temperature requires shock speeds (~ 200 km s⁻¹) that are much larger than the typical line widths that we have observed in the DIM. Certainly, the hot gas seen in the X-ray data may cool and fall back into the disk, thereby contributing to the DIM.

4.2. The Dynamics and Inferred Vertical Extent of the DIM

The observed Hα and [N II] λ6584 line widths in the DIM range from ~ 30–100 km s⁻¹ (FWHM), which are rather similar to the line widths in the Reynolds Layer in our own Galactic disk of ~ 30–60 km s⁻¹ (Reynolds 1985). Since we have verified that there are no significant velocity shears along the slit in the regions where we have made these line widths measurements, the broadening must be due to small-scale “turbulent” motions of the gas. The lines are certainly broader than pure thermal broadening (which is only 22 km s⁻¹ FWHM for H I at T = 10⁵ K). Of course, the [O III] λ5007 line widths are larger still: typically 70–150 km s⁻¹ FWHM.

We can use these line widths to estimate the corresponding scale height of the emitting gas, assuming that the gas clouds have an isotropic velocity dispersion and move in a gravitational potential in which they act as test particles. Using optical surface photometry of the disks of our sample galaxies and taking mass-to-light ratios M₀/L = 5 solar units for both V and B bands (see, e.g., Binney & Tremaine 1987), we estimate that the typical surface mass-density in the inner disks ranges from 100–400 M₀ pc⁻². We further assume that the mass that sets the potential has the form ρ(z) ∝ exp [−z/H], where z is the distance out of the midplane and H is the scale height for the mass, ρ. In the disk of the Milky Way, H ~ 350 pc (Freeman 1978). Adopting this value, we have then solved for the scale height, hgas, for an ensemble of gas clouds moving in this potential with a velocity dispersion in the z-direction σ_z = 0.43 × (FWHM). The results are listed in Table 7.

From this we see that typical scale heights for the quiescent DIM (based on Hα and [N II] λ6584 line widths) are 300–500 pc, which is significantly less than the values of 600–900 pc for the Reynolds Layer (Reynolds 1993). This is due in part to the much larger surface-mass densities in the inner regions of our galaxies and the associated deeper potential well. The estimated scale heights for the dominant (quiescent) component of the DIM are in fact typically comparable to our assumed scale height for the stellar disk (350 pc). Thus, we conclude that the DIM in the inner regions of our galaxies is not in any sense an “extraplanar” phenomenon. This is interesting, since the terms DIM (or DIG or WIM!) and “extraplanar gas” were often used synonymously in early investigations. In fact, the quiescent state we find for the dominant component of the DIM may naturally explain why the DIM seems to be ubiquitous in late-type galaxies, but striking examples of extraplanar gas are proving to be rare (see, e.g., Rand 1996a, 1996b).

In Table 7 we also list the derived scale heights for the disturbed DIM using our measured [O III] λ5007 line widths. These scale heights are typically 400–800 pc, or a factor of ~ 1.5–2 greater than for the quiescent DIM. Thus the disturbed DIM might more properly be considered “extraplanar.” In this regard, it is intriguing that Rand (1997) found morphological evidence for two components in the DIM in NGC 891. Since this galaxy is viewed almost exactly edge-on, Rand fitted the vertical dependence of the mean Hα surface brightness in terms of the sum of two exponentials. There is a bright component that provides
The range of the FWHMs of the DIM emission lines Hα (for cases in which the Hα equivalent width Hα EW is larger than 3 Å) and [N II] λ6583 (when the Hα EW is less than 3 Å). The observed values are equated to those in the z direction by assuming isotropic motion of the gas.

3. Scale height of the diffuse gas corresponding to the FWHMs of the Hα and [N II] lines, calculated assuming an exponential distribution of mass in the z direction with a scale height of 350 pc. See text for further details.

4. The range of the FWHM of the DIM emission line [O III] λ5007. The observed values are equated to those in the z direction by assuming isotropic motion of the gas.

5. Scale height of the diffuse gas corresponding to the FWHMs of the [O III] λ5007 line, calculated assuming an exponential distribution of mass in the z direction with a scale height of 350 pc. See text for further details.

\[ \sum^a \rho_\text{star} (M_\odot \text{ pc}^{-2}) \]

\[ \Delta V_{\text{H}^\alpha, \text{N}^\text{II}} \]

\[ H_{\text{H}^\alpha, \text{N}^\text{II}} \]

\[ \Delta V_{\text{O III} \lambda5007} \]

\[ H_{\text{O III} \lambda5007} \]

Table 7

| Object       | \( \Sigma^a \) (\( M_\odot \text{ pc}^{-2} \)) | \( \Delta V_{\text{H}^\alpha, \text{N}^\text{II}} \) (km s\(^{-1}\)) | \( H_{\text{H}^\alpha, \text{N}^\text{II}} \) (pc) | \( \Delta V_{\text{O III} \lambda5007} \) (km s\(^{-1}\)) | \( H_{\text{O III} \lambda5007} \) (pc) |
|--------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| M51          | 200                             | 80–100                          | 470–620                         | 110–170                         | 700–1300                        |
| M81          | 150                             | 60–150                          | 400–1300                        | 60–120                          | 250–560                         |
| M101         | 340                             | 30–90                           | 120–400                         | 60–160                          | 300–1000                        |
| NGC 2403     | 250                             | 50–60                           | 240–300                         | 60–160                          | 300–1000                        |
| NGC 4395     | 94                              | 40–60                           | 330–530                         | ...                             | ...                             |

\[ V_0 \approx 84\% \text{ of the total emission and has a scale height of 500 pc and a faint component that provides the other 16\% of the emission and has a scale height 5–6 times larger. The bright and faint components must have different kinematics to have such different vertical distributions, and we suggest that they may correspond, respectively, to the quiescent and disturbed components of the DIM that we have identified kinematically. It would be important in this regard to measure the dependence of the [O III] \( \lambda5007/H\beta \) ratio on distance out of the midplane in NGC 891 to see if the more extended DIM component has a relatively high ionization state (as we find for the disturbed DIM). The only published [O III] measurement (Dettmar 1992) is an upper limit at a distance of only 0.5 kpc out of the disk (in the region dominated by Rand’s inner DIM component, which we would predict to be of low ionization).

5. SUMMARY

We have reported on the initial results from a program to study the morphology, physical state, and kinematics of the diffuse ionized medium (DIM) in a sample of the nearest and brightest late-type galaxies. For each of five galaxies (NGC 2403, M81, NGC 4395, M51, and M101) we have analyzed deep narrowband Hα images covering essentially the entire star-forming disk (a field diameter of 23.2 or 18–53 kpc). These images reach limiting Hα surface brightnesses of \( \approx 8 \times 10^{-17} \) to \( 18 \times 10^{-17} \) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\) (corresponding to an emission measure of \( \approx 40–90 \) cm\(^{-6}\) pc). We have also analyzed long-slit spectra covering a single region in the inner disk (5' or 4–12 kpc in extent centered on the galactic nucleus). These spectra cover the H\β and [O III] \( \lambda5007 \) emission lines at a velocity resolution of \( \approx 75 \) km s\(^{-1}\) (FWHM) and the [O I] \( \lambda6300, \text{H}^{\alpha}, [\text{N II}] \lambda6584, \) and [S II] \( \lambda6717, 6731 \) emission lines at a velocity resolution of \( \approx 40 \) km s\(^{-1}\). By summing the spectra over large spatial regions, we have been able to measure emission lines down to a limiting surface brightness (5σ) of \( \approx 5 \times 10^{-18} \) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\) (an emission measure of 2.5 cm\(^{-6}\) pc for Hα).

As in the case of other similar galaxies (see, e.g., Ferguson et al. 1996b; Hoopes et al. 1996), we find that diffuse low surface brightness gas (a DIM) covers most of the star-forming disk and is morphologically related to the presence of high surface brightness gas (the giant H II regions). Plots of the cumulative contribution of gas of progressively higher surface brightness to the integrated Hα flux are very similar to the plots for galaxies in the Sculptor group (Hoopes et al. 1996). We note that the D in DIM stands for “diffuse” and utilize the ratio of the mean/rms Hα surface brightness to quantify this. M51 is an example of a galaxy with a pronounced DIM as defined by morphology but a weak DIM as defined by absolute surface brightness (it has lots of diffuse, high surface brightness emission). It is not yet clear whether surface brightness or morphology is the more physically meaningful way to specify the DIM.

We find that the DIM and the regions of high Hα surface brightness (giant H II regions) differ systematically in their physical and dynamical state. The DIM is characterized by enhanced emission (relative to Hα) in the low-ionization forbidden lines ([O I], [N II], and [S II]). This agrees with results for the DIM in other galaxies including our own (cf. Dettmar 1992 and references therein). However, we also find that the high-ionization [O III] \( \lambda5007 \) line is moderately strong ([O III] \( \lambda5007/H\beta \approx 1 \) in the DIM. This contrasts with upper limits on the [O III] surface brightness in our own Galaxy and the prototypical edge-on spiral NGC 891 (Reynolds 1990; Dettmar 1992). We directly verify the inference made by Lehnert & Heckman (1994) that the DIM contributes significantly to the spatially integrated (global) emission-line spectra of late-type galaxies as published by Kennicutt (1992a, 1992b).
We also find that the DIM is more disturbed kinematically than the gas in the giant H II regions. The deconvolved (intrinsic) widths of the H$_z$ and [N II] $\lambda$6584 lines range from 30 to 100 km s$^{-1}$ (FWHM) in the DIM compared to 20–50 km s$^{-1}$ in the giant H II regions. These can be compared to a width of 22 km s$^{-1}$ for pure thermal broadening of H$_z$ at $T = 10^4$ K. The high-ionization gas in the DIM is more kinematically disturbed than the low-ionization gas: in the same regions in the DIM, we measure broadening of H$_z$ for the majority ($\gtrsim$80%) of the emission in lines such as H$_z$, H$_\beta$, [N II] $\lambda$6584, and [S II] $\lambda$6717, 6731, and a “disturbed DIM” that is responsible for the bulk of the [O III] $\lambda$5007 emission. Considerations of hydrostatic equilibrium in the vertical potential well of the inner disk then imply that the quiescent DIM has a modest scale height of several hundred pc (probably similar to the scale height of the old stars). Thus, the terms “DIM” and “extraplanar gas” are by no means synonymous. The estimated scale heights for the disturbed DIM are about a factor of 2 larger ($0.3–1$ kpc). This material would have a higher characteristic ionization state than the quiescent (thin-disk) DIM.

We find that the standard leaky H II region model in which the DIM is photoionized by the diffuse Lyman continuum radiation field from O stars (see Domgørgen & Mathis 1994; J. Sokolowski 1993, private communication) can naturally account for the measured properties of the quiescent DIM. The ubiquity of faint H$_z$ emission (which our spectra show to fill essentially the entire inner disk) then leads to an apparent need for some fine-tuning of the physical state of the ISM: the disk must be optically thick enough to capture most of the ionizing photons, yet optically thin enough to allow these photons to permeate the disk. Why is this so? Is there some feedback loop involving massive stars and the ISM?

In contrast, mechanical heating (which is ultimately driven by the energy supplied by supernovae and stellar winds) is the most natural ionization source for the disturbed DIM. Either radiative shocks (with a shock speed $>100$ km s$^{-1}$) or turbulent mixing layers (Slavin, Shull, & Begelman 1993) can produce relatively strong [O III] $\lambda$5007 emission. Since the disturbed DIM accounts for only a minority ($\lesssim$20%) of the H$_z$ emission in the regions we have studied, there is no fundamental energetics problem in either case. However, the observed surface brightness of the disturbed DIM requires that essentially every line of sight through the inner disk must encounter at least one shock or 10 turbulent mixing layers. Direct observational evidence for such a large areal covering factor of mechanically heated gas in typical galaxy disks is mixed (Heiles 1990; Oey & Clarke 1997; but see Snowden & Pietsch 1995).

We also have stressed that there is no clear discontinuity in physical and dynamical properties of the giant H II regions and the quiescent DIM. The quiescent DIM is morphologically related to the giant H II regions and there is a smooth dependence of the emission-line ratios and emission-line widths on the surface brightness of the emission. In other words, as one moves outward from the H II regions into the DIM, the properties of the ionized gas change in a continuous, regular way. The present data on the disturbed DIM are too limited to make firm statements in this regard, but we are currently investigating this in a much more extensive new data set. In any case, we suggest that a unified view of the warm ionized gas in the disks of star-forming galaxies is likely to be productive.

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FIG. 3a

FIG. 3.—Gray-scale representation of the DIM two-dimensional spectra. The y-axis is the wavelength coordinate increasing from top to bottom. The x-axis is along the slit. From left to right, the axis points toward northwest for M101 and toward southwest for the rest galaxies. The length of each window is ~5'. (a) The strong emission lines [N II] $\lambda$6548, Hα, and [N II] $\lambda$6584. The [S II] $\lambda\lambda$6717, 6731 lines for NGC 4395 are included to complement the weak [N II] lines. (b) The weaker lines Hβ, [O III] $\lambda$5007, and [O I] $\lambda$6300. The data for those galaxies that have poor S/N in these emission lines are not shown.

WANG, HECKMAN, & LEHNERT (see 491, 123)
FIG. 3b

WANG, HECKMAN, & LEHNERT (see 491, 123)