LYMAN CONTINUUM EXTINCTION BY DUST IN H II REGIONS OF GALAXIES

AKIO K. INOUE
Department of Astronomy, Faculty of Science, Kyoto University, Sakyoku, Kyoto 606-8502, Japan; inoue@kusastro.kyoto-u.ac.jp
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ABSTRACT

We examine Lyman continuum extinction (LCE) in H II regions by comparing infrared fluxes of 49 H II regions in the Galaxy, M31, M33, and the Large Magellanic Cloud with estimated production rates of Lyman continuum photons. A typical fraction of Lyman continuum photons that contribute to hydrogen ionization in the H II regions of three spiral galaxies is \( \leq 50\% \). The fraction may become smaller as the metallicity (or dust-to-gas ratio) increases. We examine the LCE effect on estimated star formation rates of galaxies. The correction factor for the Galactic dust-to-gas ratio is 2–5.

Key words: dust, extinction — galaxies: ISM — H II regions — infrared radiation — radio continuum — stars: formation

1. INTRODUCTION

Dust grains exist everywhere—from the circumstellar environment to interstellar space. Hence, radiation from celestial objects is always absorbed and scattered by dust grains. Without a correction for the dust extinction, we inevitably underestimate the intrinsic intensity of the radiation, and our understanding of the physics of these objects may be misleading. Thus, dust extinction for nonionizing photons (\( \lambda > 912 \) Å) in the interstellar medium (ISM) has been well studied to date (e.g., interstellar extinction curve: Savage & Mathis 1979; Seaton 1979; Calzetti, Kinney, & Storchi-Bergmann 1994; Gordon et al. 2000).

In H II regions, Lyman continuum (LC) photons also suffer extinction by dust grains (e.g., Ishida & Kawajiri 1968; Harper & Low 1971). We refer to this other type of extinction as the Lyman continuum extinction (LCE). Indeed, the fraction of LC photons absorbed by dust in H II regions can be large (e.g., Petrosian, Silk, & Field 1972; Panagia 1974; Mezger, Smith, & Churchwell 1974; Natta & Panagia 1976; Sarazin 1977; Smith, Biermann, & Mezger 1978; Aannestad 1989; Shields & Kennicutt 1995; Bottorff et al. 1998). Petrosian et al. (1972), for example, have estimated the fraction of LC photons contributing to hydrogen ionization to be only 0.26 in the Orion Nebula.

If a large number of LC photons are absorbed by dust in H II regions, the effect of the LCE on estimating the star formation rate (SFR) will be very large. This is because we can only estimate the number of ionizing photons, LC photons used for hydrogen ionization, from the observation of hydrogen recombination lines or thermal radio continuum. When we define the fraction of ionizing photons as \( f \), we obtain

\[
N_{LC} = fN'_{LC},
\]

where \( N_{LC} \) and \( N'_{LC} \) are the intrinsic and apparent production rates of LC photons, respectively. Unless we correct the observed data for the LCE, we cannot obtain the actual LC photon production rate, and then the true SFR. Therefore, we should estimate the fraction, \( f \), in H II regions. However, the LCE was not discussed in the context of estimating the SFR of galaxies before Inoue, Hirashita, & Kamaya (2001a, hereafter Paper I).

Paper I has proposed two independent methods for estimating \( f \) and applied the methods to the Galactic H II regions. Then they have shown that there are a number of H II regions with \( f \leq 0.5 \) in the Galaxy. Moreover, they have found that \( f \) can be approximated as a function of dust-to-gas ratio only. If the approximation can be applied to the nearby spiral galaxies and their observed dust-to-gas ratios are adopted, \( f \) averaged over a galactic scale is about 0.3. Therefore, the SFR corrected for the LCE effect is 3 times larger than the uncorrected SFR.

The aim of this paper is to confirm these results of Paper I, not only for H II regions in our Galaxy but also for extragalactic H II regions. We also discuss whether the effect of the LCE on estimating the SFR of galaxies is really important. We describe the method for estimating \( f \) in § 2. Then \( f \) is determined for the H II regions in the Local Group galaxies in § 3. We discuss the dependence of \( f \) on the dust-to-gas ratio in § 4, and our conclusions are summarized in the final section.

2. METHOD FOR ESTIMATING THE EFFECT OF LCE

To estimate \( f \) in equation (1) for each H II region, the apparent production rate of LC photons in each region, \( N_{LC} \), is compared with its IR luminosity, \( L_{IR} \). (For the relation between the IR excess and \( f \), see the Appendix.) In this paper, we use a method for estimating \( f \) presented in § 3 of Paper I.

According to equation (12) in Paper I, we obtain

\[
f = \frac{0.44 + 0.56e}{0.28 + 5.6(L_{IR}7/N_{LC,50})},
\]

where \( e \) denotes the average efficiency of dust absorption for nonionizing (\( \lambda > 912 \) Å) photons, and \( L_{IR,7} \) and \( N_{LC,50} \) are the IR luminosity and LC photon production rate normalized by \( 10^7 \) \( L_{\odot} \) and \( 10^{50} \) s\(^{-1} \), respectively. The equation is based on the theory of IR emission from H II regions by Petrosian et al. (1972) and the following discussion by Inoue, Hirashita, & Kamaya (2000).\(^1\) It is also worthwhile to note that \( L_{IR,7}/N_{LC,50} \) is proportional to the flux ratio of the IR emission to the thermal radio emission, H\( \alpha \) line, etc. If we express in the form of the flux ratio, the determination of \( f \) is free from the uncertainty of the distance to the object.

Here we describe some assumptions adopted in the derivation of equation (2). Since \( L_{IR} \) is the total energy emitted by dust, the wavelength range is set to 8–1000 \( \mu m \), which

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\(^1\) See also Inoue, Hirashita, & Kamaya 2001b.
covers almost all that wavelength range of dust emission. Also, it is supposed that the IR radiation from H II regions is dominated by large (~0.1 μm) grains in thermal equilibrium with the ambient radiation field. In other words, we neglect the contribution to the total IR luminosity of very small grains (≤0.01 μm) and polycyclic aromatic hydrocarbons (PAHs), which emit mainly in the mid-infrared (MIR, 8–40 μm; e.g., Dwek et al. 1997). In principle, this assumption would make us underestimate the total IR luminosity of dust in H II regions because such MIR emission is observed from these regions (e.g., Pišć & Mampaso 1991; DeGioia-Eastwood 1992; Leisawitz et al. 1998). Fortunately, it seems that the contribution of the MIR luminosity to that of the total IR is small enough to be neglected (Fig. 1 in Leisawitz et al. 1998). Thus, the IR spectral energy distribution (SED) of H II regions is assumed to be a modified blackbody function with one temperature throughout the paper.

Moreover, we do not take account of the existence of helium. This is because almost all (96%, according to Mathis 1971) photons produced by helium recombination can ionize neutral hydrogen. We do not consider the escape of LC photons from H II regions, either. Indeed, less than 3% of LC photons can escape from the star-forming regions in nearby galaxies (Leitherer et al. 1995). In short, we deal with an ideal H II region that consists of only hydrogen and dust, where no LC photons leak.

Let us determine $\epsilon$, which denotes the average efficiency of dust absorption for nonionizing photons. The total (absorption and scattering) optical depth of dust, $\tau_\lambda$, is expressed by

$$\tau_\lambda = \frac{\tau_\lambda^{abs}}{1 - \omega_\lambda} = \frac{A_\lambda}{2.5 \log \epsilon}, \quad (3)$$

where $\tau_\lambda^{abs}$, $\omega_\lambda$, and $A_\lambda$ are the absorption optical depth of dust, the dust albedo, and the amount of extinction at wavelength $\lambda$, respectively. We can determine $A_\lambda$ from an extinction curve, $X_\lambda$, and its normalization, $E(B-V)$, i.e., $X_\lambda = A_\lambda/E(B-V)$. The efficiency of dust absorption at wavelength $\lambda$, $\epsilon_\lambda$, is defined as

$$\epsilon_\lambda \equiv 1 - e^{-\tau_\lambda^{abs}} = 1 - 10^{-0.4X_\lambda(E(B-V))(1-\omega_\lambda)}. \quad (4)$$

Then averaging $\epsilon_\lambda$ over $\lambda$ with and weighting by the intrinsic stellar flux density yields the average efficiency, $\epsilon$.

We show $\epsilon$ as a function of $E(B-V)$ in Figure 1. In this calculation, we set the stellar spectrum to be simply that of the blackbody at 30,000 K. Changing the temperature does not alter the result significantly. For example, if we choose 50,000 K as the effective temperature of stars, the value of $\epsilon$ increases by a factor of about 1%. The calculation of the average is performed from 1100 to 3500 Å. We adopt two types of the interstellar extinction curve, $X_\lambda$: one is that in our Galaxy (Seaton 1979); the other is that in the Large Magellanic Cloud (LMC; Howarth 1983). These two cases are shown in Figure 1 by the solid and dashed lines, respectively. Moreover, we set the dust albedo to be a constant of 0.5 for simplicity, although it varies with wavelength (Witt & Lillie 1973; Lillie & Witt 1976). The results in this case are shown by the thick lines. Also, the results without scattering (i.e., $\omega_\lambda = 0$) are shown by the thin lines for comparison.

Once we determine $\epsilon$ for H II regions from Figure 1, we can estimate $f$ from the ratio of the IR luminosity to the observed LC photon production rate via equation (2). In the next section, we will examine $f$ for H II regions in some Local Group galaxies.

3. FRACTION $f$ OF H II REGIONS IN THE LOCAL GROUP GALAXIES

To determine $f$, the data of the IR luminosity and the production rate of LC photons for the individual H II region are required. But when we compare two photometric data we must match their apertures and resolutions, because in general different observations have different aperture and resolution. This prevents us from constructing uniform data of a large number of H II regions. These effects produce one of the largest uncertainties in the current analysis.

We have gathered the data that allow us to estimate $f$ with proper accuracy, though the sample size is rather small. In this section, we estimate $f$ for H II regions in our Galaxy, M31, M33, and the LMC.

3.1. Our Galaxy

Suitable data for our analysis have been compiled by Wynn-Williams & Becklin (1974). The data are read out from their Figure 9 directly, and are listed in Table 1. Column (1) lists the name of the H II regions. Since two separate components of W3, W51, and NGC 6537 are plotted in Figure 9 of Wynn-Williams & Becklin (1974), we list both components of these regions in Table 1. Columns (2) and (3) list the logarithmic production rate of LC photons estimated from radio observations and far-infrared (FIR) (40–350 μm) luminosity, respectively. The FIR (40–350 μm) luminosity is almost equal to the total IR (8–1000 μm) luminosity if the dust SED is assumed to be the

\[ \text{FIR} (40–350 \, \mu \text{m}) \text{ luminosity} \approx \text{total IR} (8–1000 \, \mu \text{m}) \text{ luminosity} \]

\[ \text{estimated production rate of LC photons} \]

\[ \text{observed LC photon production rate} \]

\[ \text{result of no scattering.} \]

\[ \text{average} \]

\[ \text{samples} \]

\[ \text{results} \]

\[ \text{dashed lines} \]

\[ \text{thick lines} \]

\[ \text{result} \]

\[ \text{data} \]

\[ \text{number} \]

\[ \text{effects} \]

\[ \text{uncertainties} \]

\[ \text{analysis} \]

\[ \text{allow} \]

\[ \text{estimate} \]

\[ \text{accuracy} \]

\[ \text{sample size} \]

\[ \text{section} \]

\[ \text{estimate} \]

\[ \text{regions} \]

\[ \text{Galaxy, M31, M33, and the LMC.} \]

\[ \text{LMC} \]

\[ \text{Magellanic Cloud} \]

\[ \text{LMC} \]

\[ \text{Howarth} \]

\[ \text{1983} \]

\[ \text{cloud} \]

\[ \text{Howarth} \]

\[ \text{1983} \]

\[ \text{large} \]

\[ \text{number} \]

\[ \text{effects} \]

\[ \text{produce} \]

\[ \text{one of} \]

\[ \text{largest} \]

\[ \text{uncertainties} \]

\[ \text{current} \]

\[ \text{analysis} \]

\[ \text{gathered} \]

\[ \text{data} \]

\[ \text{allow} \]

\[ \text{estimate} \]

\[ \text{proper} \]

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\[ \text{size} \]

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\[ \text{section} \]

\[ \text{estimate} \]

\[ \text{regions} \]

\[ \text{Galaxy, M31, M33, and the LMC.} \]
TABLE 1

The Galactic H II Regions

| Object ID | \( \log N_{LC}^{1} \) | \( \log L_{FIR}^{1} \) | \( L_{\text{IR}}/L_{\text{LC}}^{1} \) | \( f \) |
|-----------|-----------------|-----------------|-----------------|-----|
| NGC 2024  | 47.7 4.3        | 0.40            | 0.40            |
| W3        | 48.2 5.3        | 1.26            | 0.14            |
| W3        | 49.4 6.1        | 0.50            | 0.32            |
| M8        | 48.3 4.7        | 0.25            | 0.59            |
| NGC 6357  | 48.4 5.2        | 0.63            | 0.26            |
| NGC 6357  | 48.4 5.0        | 0.35            | 0.44            |
| IC 4628   | 48.6 5.4        | 0.63            | 0.26            |
| Orion     | 48.7 5.2        | 0.35            | 0.44            |
| G345.4-0.4 | 48.7 5.5       | 0.66            | 0.29            |
| G351.6    | 48.8 5.8        | 1.12            | 0.15            |
| G59-0.4   | 49.1 5.6        | 0.32            | 0.49            |
| W75/DR 21 | 49.2 5.3        | 1.03            | 1.01            |
| RCW 117   | 49.5 6.1        | 0.35            | 0.44            |
| G351.6+0.2 | 49.7 5.1       | 0.25            | 0.59            |
| W58       | 49.7 6.0        | 0.20            | 0.71            |
| G351.6-1.3 | 49.8 6.3       | 0.32            | 0.49            |
| W51       | 49.8 6.2        | 0.25            | 0.59            |
| W51       | 50.4 6.9        | 0.32            | 0.49            |
| RCW 122   | 49.9 6.3        | 0.25            | 0.59            |
| Sgr C     | 50.0 6.8        | 0.63            | 0.26            |
| M17       | 50.1 6.5        | 0.25            | 0.59            |
| Sgr B     | 50.5 7.1        | 0.35            | 0.44            |
| W49       | 50.7 7.3        | 0.35            | 0.44            |

Note—Col. (1): Two separate components in W3, W51, and NGC 6357 are both listed; Col. (2): LC photon production rates estimated from radio observations; Col. (3): observed FIR luminosities; Col. (4): ratios of \( L_{\text{IR}}/L_{\text{LC}}^{1} \); Col. (5): estimated ratio of \( L_{\text{IR}}/L_{\text{LC}}^{1} \); Col. (6): estimated ratio of \( L_{\text{IR}}/L_{\text{LC}}^{1} \); Col. (7): estimated \( f \) from eq (2) by assuming \( \epsilon = 1 \).

modified blackbody function with the temperature of 30 K and the emissivity index of 1.

Since \( E(B-V) \sim 1 \) for the Galactic H II regions (e.g., Caplan et al. 2000), Figure 1 tells us that \( \epsilon \approx 1 \), even in the case with the scattering for nonionizing photons. Thus, we can safely assume \( \epsilon = 1 \) for the Galactic H II regions, so that we can determine \( f \) of these regions via equation (2) (see col. [5]). The mean value of \( f \) is 0.45. Thus, we find that about half the LC photons are absorbed by dust in H II regions. This is one of the results in Paper I.

3.2. M31

Xu & Helou (1996) have studied the properties of discrete FIR sources in M31 by using the IRAS HiRes image (Aumann, Fowler, & Melnyk 1990; Rice 1993). Thirty-nine sources are extracted from the 60 \( \mu \)m map. They have also examined the correlation between these FIR sources and H\( \alpha \) sources presented by Walterbos & Braun (1992). Since Walterbos & Braun (1992) have surveyed only the northeast half of M31, 12 out of 39 FIR sources have H\( \alpha \) counterparts. These twelve FIR sources make the sample for the current analysis. In Table 2, some properties of the sample H II regions in M31 are listed.

Column (2) of Table 2 lists the measured flux density at 60 \( \mu \)m. Unfortunately, for almost all sample regions only the 60 \( \mu \)m flux densities are available. Hence, we estimate total IR luminosity of dust emission in each region from the 60 \( \mu \)m flux density in the following way. Assuming the IR SED of these FIR sources is the modified blackbody function with temperature 30 K and emissivity index 1, we obtain \( L_{\text{IR}}/L_{\text{LC}} = 3.50 \times [D/(1 \text{kpc})]^{2} \times [F_{60 \mu m}/(1 \text{Jy})] \), where the wavelength range of the IR luminosity, \( L_{\text{IR}} \), is 8–1000 \( \mu \)m, and \( D = 760 \) kpc is the adopted distance to M31. The derived IR luminosities are shown in column (3) of Table 2. The adopted dust temperature, 30 K, is reasonable because the dust temperature of 10 isolated H II regions whose flux densities at both 60 and 100 \( \mu \)m are listed in Table 3 of Xu & Helou (1996) is estimated to be 29 K on average.

Since the angular resolution of a H\( \alpha \) image is much higher than that of a 60 \( \mu \)m image, numerous H\( \alpha \) sources are included in the area over which the flux density of one FIR source at 60 \( \mu \)m is integrated. The sum of the H\( \alpha \) fluxes in the area of each FIR source is shown in column (4) of Table 2. These values are corrected for the [NII] contamination by assuming a constant ratio of [NII]/H\( \alpha \) = 0.3 (Walterbos & Braun 1992).

When we estimate the production rate of LC photons from H\( \alpha \) flux, we must correct it for the interstellar extinction. Walterbos & Braun (1992) have commented that the
mode of the interstellar extinction at Hz is 0.8 mag. Since this mode of extinction is estimated from the column density of HI gas, it is a typical extinction averaged over the ISM of M31. If we assume case B and a gas temperature of 10,000 K (Osterbrock 1989), we obtain \( N_{\text{LC}} \) from the HI column density. The HI flux in the ring of M31 is estimated to be \( 8.8 \times 10^{22} \text{cm}^{-2} \) [\( F_{\text{HI}}/1 \text{ erg s}^{-1} \text{ cm}^{-2} \)] × 10^{0.4A_H}, where \( F_{\text{HI}} \) is the HI flux (col. [4]) and \( A_H = 0.8 \) mag is the assumed amount of extinction at the Hz line. The derived \( N_{\text{LC}} \) is listed in column (5). The ratio of the IR luminosity to the LC photon production rate is shown in column (6).

Now, we need to estimate \( \epsilon \). By adopting \( A_V/E(B-V) = 3.1 \) and the Galactic extinction curve, \( E(B-V) \) is \( \sim 0.3 \) mag when \( A_H \sim 0.8 \) mag. Then we can assume \( \epsilon = 0.7 \) for the H II regions in M31 from the line for the dust albedo of 0.5 in Figure 1. Finally, we determine \( f \) via equation (2) (col. [7]). The mean \( f \) is 0.38, which is almost equal to that of the Galactic H II regions.

Also, Devereux et al. (1994) have compared the Hz emission map with the IR emission map produced by the maximum correlation method (IRAS HiRes image). They divided the Hz emission into three components: the star-forming ring, the bright nucleus, and a diffuse (unidentified) component. The star-forming ring, whose diameter is 1.65, has the observed Hz + [N II] luminosity of \( 4.77 \times 10^6 \text{L}_\odot \). They estimated its IR (8–1000 \( \mu \)m) luminosity to be \( 1.08 \times 10^9 \text{L}_\odot \) by assuming the modified blackbody function with 26 K and index 1. If we regard the star-forming ring as an aggregation of a lot of H II regions and assume \( A_H = 0.8 \) mag and \([\text{N II}]/\text{Hz} = 0.3\), we obtain \( L_{\text{IR},7}/N_{\text{LC},50} \sim 0.5 \) for the ring. This corresponds to \( f \sim 0.3 \) when \( \epsilon = 0.7 \). The value of \( f \) shows good agreement with the mean \( f \) of the sample in Table 2.

3.3. M33

We find suitable data for H II regions in M33 in Devereux, Duric, & Scowen (1997), who examine the correlation between Hz, FIR, and thermal radio emission of M33. They have reported some properties of isolated H II regions. We determine \( f \) of these regions. The sample properties are listed in Table 3.

In column (2), FIR (40–1000 \( \mu \)m) luminosities of the H II regions, which are determined from the flux densities at 60 and 100 \( \mu \)m measured from IRAS HiRes images, are presented. In column (3), the 5 GHz flux densities (see also Duric et al. 1993) are shown, and the estimated LC photon production rates are listed in column (4) via \( N_{\text{LC}}/1 \text{ s}^{-1} = 8.88 \times 10^{46}[D/(1 \text{ kpc})]^2 \left[F_{\text{5 GHz}}/(1 \text{ Jy})\right] \) (Condon 1992). For the distance to M33, 840 kpc is adopted. If the dust SED can be fitted by a modified blackbody function (with emissivity index 1 and at 30 K), we have \( L_{\text{FIR}} \) (40–1000 \( \mu \)m) \( \approx I_{\text{IR}} \) (8–1000 \( \mu \)m). We determine the ratio of the IR luminosity to the photon production rate under this assumption (col. [5]).

Devereux et al. (1997) have also commented on the properties of the interstellar extinction for the H II regions in M33. They have compared Hz emission with thermal radio emission and argued in their Figure 7 that the average extinction is \( A_V \sim 1 \) mag (i.e., \( A_H \sim 0.8 \) mag), although there is a large dispersion corresponding to \( \pm 1 \) mag. Thus, we can assume \( \epsilon = 0.7 \) for all the sample regions in M33, as well as those in M31. The determined values of \( f \) are listed in column (6) of Table 3. The mean is 0.41, although the large dispersion of the interstellar extinction may cause a large dispersion of \( f \).

Thus, we saw that \( f \sim 0.4 \) or less for the H II regions in M31 and M33. Hence, we conclude that the typical values of \( f \) in these galaxies are nearly equal to that in our Galaxy. Therefore, we suggest that the fraction of LC photons consumed by dust in the H II regions of other spiral galaxies, as well as that in the Galaxy, M31, and M33, may be \( \gtrsim 50\% \).

3.4. LMC

DeGioia-Eastwood (1992) have provided the data for six H II regions in the LMC. The IR flux densities of the sample regions have been measured from the co-added survey data by IRAS. Relatively isolated regions have been chosen as the sample regions to perform a reasonable subtraction of the background flux. DeGioia-Eastwood (1992) has reported the IR, Hz, and radio fluxes of the sample regions whose apertures have been matched carefully among images of different wavelengths. The properties of the data are shown in Table 4.

Columns (2) and (3) list IRAS 60 and 100 \( \mu \)m flux densities, respectively. The IR (8–1000 \( \mu \)m) luminosity is calculated from these flux densities via \( L_{\text{IR}}/L_{\odot} = 0.61 \times [D/(1 \text{ kpc})]^2 [2.58F_{\text{600}}/(1 \text{ Jy})] + [F_{\text{1000}}/(1 \text{ Jy})] \). Here we assume the dust SED to be a modified blackbody function with 30 K and index 1, that is, \( L_{\text{IR}} \) (8–1000 \( \mu \)m) \( \approx 1.66L_{\text{FIR}} \) (40–120 \( \mu \)m). Then the estimated total IR luminosities are shown in column (4). The adopted distance to the LMC is 51.8 kpc.

### Table 3

| Object     | \( L_{\text{FIR}} \) (10^7 \( \text{L}_\odot \)) | \( F_{\text{5 GHz}} \) (mJy) | \( N_{\text{LC}} \) (10^5 s^{-1}) | \( L_{\text{IR}}/N_{\text{LC}} \) (10^7 \( \text{L}_\odot/10^5 \text{s} \)) | \( f \) |
|------------|-----------------|------------------|-------------------|--------------------------------------|------|
| VGHC 20, 25... | 0.56 | 0.08 | 0.50 | 1.12 | 0.13 |
| IC 131 ...    | 1.50 | 0.7 | 0.44 | 2.27 | 0.064 |
| IC 133 ...    | 1.67 | 6.6 | 4.14 | 0.40 | 0.33 |
| NGC 595 ...   | 0.79 | 18.0 | 11.3 | 0.070 | 1.23 |
| IC 46, 52 ... | 1.34 | 1.8 | 1.13 | 1.19 | 0.12 |
| IC 104 ...    | 0.58 | 1.1 | 0.69 | 0.84 | 0.17 |
| NGC 97, 98 ...| 0.47 | 4.5 | 2.82 | 0.17 | 0.67 |
| NGC 604 ...   | 7.50 | 60.0 | 37.6 | 0.20 | 0.59 |

**Note:** Col. (1): Object name; Col. (2): FIR luminosities determined from IRAS HiRes images of 60 and 100 \( \mu \)m by adopting the distance of 840 kpc; Col. (3): observed 5 GHz flux densities; Col. (4): LC photon production rates estimated from Col. (3) by adopting the distance of 840 kpc; Col. (5): ratios of IR luminosity to LC photon production rates; Col. (6): estimated \( f \) from eq. (2) by assuming \( \epsilon = 0.7 \).
From the flux densities at 5 GHz in column (5), the production rates of LC photons are calculated via Condon’s formula in § 3.3 (col. [6]).

The color excess of each region, $E(B - V)$, estimated from the observed Balmer decrement and corrected for foreground reddening is listed in column (8). Using the line of the LMC extinction law and the dust albedo of 0.5 in Figure 1, we obtained the value of $\epsilon$ from each $E(B - V)$ (col. [9]). Finally, $f$ is determined for each sample region (col. [10]). The mean $f$ is 0.74. This is obviously larger than those of the Galaxy, M31, and M33.

DeGeioa-Eastwood (1992) has also determined $f$ for these regions. Her mean $f$ is $0.65 \pm 0.13$, which is consistent with that in the current paper. Here we should note that the $f$ of DeGeioa-Eastwood (1992) is determined from the dust optical depth for UV (1000–3000 Å) photons. By the definition of $f$, however, it should be determined from the dust optical depth for LC photons ($\lambda < 912$ Å), as we stated in Paper I and this paper.

On the other hand, Xu et al. (1992) have compared the IR, Hα, and radio emission from the LMC and have examined more global correlations among these emissions. They have displayed impressive contour maps of these wavelengths, which strongly make us believe that these three kinds of emission have the same origin, i.e., the star-forming regions. Indeed, there are excellent coincidences among IR, thermal radio, and Hα sources (see also Maihara, Oda, & Okuda 1979; Fürst, Reich, & Sofue 1987 for the Galactic sources). According to Xu et al. (1992), the FIR (40–120 μm) flux associated with star formation in the LMC is $28.9 \times 10^{-10}$ W m$^{-2}$, and the thermal radio flux density at 6.3 cm in the same area is 131 Jy. Since the corresponding $L_{\text{IR}}/N_{LC}$ is 0.13, $f \sim 0.7$ when we assume $\epsilon = 0.4$ (the average value for the sample in Table 4). This is in good agreement with the mean $f$ of the sample in Table 4.

Therefore, we conclude that $f$ of the H II regions in the LMC is about 0.7, larger than those in the spiral galaxies such as the Galaxy, M31, and M33. The larger $f$ may be caused by the lower metallicity of the LMC. A lower metallicity is likely to lead to a smaller dust-to-gas ratio, so the fraction of ionizing photons, $f$, increases. This issue will be discussed more thoroughly in the next section.

### 4. DISCUSSIONS

We have estimated $f$ for each H II region in some Local Group galaxies by comparing its observed IR luminosity with the production rate of LC photons. Here we discuss what the determined $f$ values suggest.

#### 4.1. Value of $f$ as a Function of Metallicity or Dust-to-Gas Ratio

First, we discuss the relationship between the mean $f$ of each galaxy and its metallicity (or dust-to-gas ratio). We naturally expect that the effect of the LCE becomes larger as the dust content increases. Then we also expect the mean $f$ of sample H II regions to be a function of the dust-to-gas ratio or metallicity of their host galaxy. To examine the issue, we summarize some parameters of each galaxy in Table 5.

The mean $f$ with its sample standard deviation is shown in column (2) of Table 5. Also, we find metallicities and dust-to-gas mass ratios of sample galaxies in columns (3) and (4), respectively. Here the metallicities are taken from van den Bergh (2000). The dust-to-gas mass ratios except for that of M31 are taken from Issa, MacLaren, & Wolfendale (1990), who have estimated the dust-to-gas ratio from the ratio of the amount of visual extinction in the surface density of H I gas. For M31, we determined the dust-to-gas ratio from the observed dust mass and gas mass directly. According to the observation of Haas et al. (1998) by the Infrared Space Observatory (ISO; Kessler et al. 1996), M31 have $3 \pm 1 \times 10^7 M_\odot$ as the dust mass. Also, M31 contains H I gas of $3.8 \times 10^8 M_\odot$ (Cram, Roberts, & Whitehurst 1980) and H$_2$ gas of $2.7 \times 10^8 M_\odot$ (Dame et al. 1993). Thus, the dust-to-gas mass ratio of M31 is

| Galaxy   | $f$        | $12 + \log (O/H)$ | $Z/S$~$N$~W~ |
|----------|------------|-------------------|---------------|
| M31 ......| 0.45 ± 0.21| 8.7               | 1.0           |
| M33 ......| 0.38 ± 0.14| 9.0               | 1.2           |
| LMC ......| 0.41 ± 0.37| 8.4               | 0.6           |
| LMC ......| 0.74 ± 0.22| 8.37              | 0.2           |

#### TABLE 4

**H II REGIONS IN LMC**

| Object | $F_{60 \mu m}$ (Jy) | $F_{100 \mu m}$ (Jy) | $L_{IR}$ ($10^3 L_\odot$) | $F_{5}$ GHz (Jy) | $N_{LC}$ ($10^6 s^{-1}$) | $L_{IR}/N_{LC}$ ($10^5 L_\odot/10^6 s^{-1}$) | $E(B - V)$ (mag) | $\epsilon$ | $f$ |
|--------|---------------------|----------------------|--------------------------|-----------------|-------------------------|-----------------------------------------------|-----------------|-------|------|
| MC 18  | 1229                | 2029                 | 8.48                     | 3.37            | 8.03                    | 0.11                                          | 0.07            | 0.28  | 0.68 |
| MC 47  | 307                 | 363                  | 1.88                     | 0.64            | 1.53                    | 0.12                                          | 0.14            | 0.47  | 0.72 |
| MC 57  | 337                 | 509                  | 2.25                     | 0.81            | 1.93                    | 0.12                                          | 0.13            | 0.45  | 0.74 |
| MC 64  | 524                 | 826                  | 3.55                     | 1.65            | 3.93                    | 0.090                                         | 0.24            | 0.66  | 1.03 |
| MC 71  | 594                 | 819                  | 3.83                     | 0.55            | 1.31                    | 0.29                                          | 0.11            | 0.39  | 0.34 |
| MC 90+91| 204                 | 382                  | 1.48                     | 0.87            | 2.07                    | 0.071                                         | 0.10            | 0.37  | 0.95 |

**Note.—Col. (1): Object name; Col. (2)–(3): IRAS co-added flux densities at 60 and 100 μm, respectively; Col. (4): IR luminosities determined fromCols. (2)–(3)—the adopted distance is 51.8 kpc; Col. (5): observed 5 GHz flux densities; Col. (6): LC photon production rates estimated from Col. (5) when the distance is adopted as 51.8 kpc; Col. (7): ratios of IR luminosity to LC photon production rates; Col. (8): $E(B - V)$ estimated from the observed Balmer decrement; Col. (9): $\epsilon$ determined from Fig. 1; Col. (10): estimated $f$ from eq. (2).
7.4 \times 10^{-3}. Moreover, the dust-to-gas ratios of sample galaxies are normalized by a typical one of the ISM in our Galaxy, $6 \times 10^{-3}$ (Spitzer 1978). In Figure 2, mean $f$ values of H II regions in each galaxy are plotted as a function of metallicity. We may find a trend that the mean $f$ decreases as the metallicity increases. We also show that mean $f$ as a function of dust-to-gas mass ratio in Figure 3. In this figure, the mean $f$ seems to become small as the dust-to-gas ratio becomes large. However, since the number of sample galaxies is still small, more investigation is needed. For example, the dependence of $f$ on metallicity will become clearer if we examine H II regions in the Small Magellanic Cloud or other metal-poor galaxies, or examine the relation of this issue to the abundance gradient of galaxies.

Let us see how the two solid lines in Figure 3 were produced. In Paper I, we have formulated the dust optical depth for LC photons, $\tau_d$, as a function of its dust-to-gas ratio

$$\tau_d = x \frac{D}{D_{MW}}, \quad (5)$$

where $\tau_d$ is evaluated over the actual ionized radius of a spherical H II region uniformly distributed dust grains (see also Hirashita et al. 2001). Here we estimate $\tau_d$ approximately at the Lyman limit. On the right-hand side, $D$ is the dust-to-gas mass ratio, which is normalized by a typical Galactic ISM value, $D_{MW} = 6 \times 10^{-3}$ (Spitzer 1978). The coefficient $x$ is a factor depending on the production rate of LC photons and the gas density of the H II region. For a galaxy having the Galactic dust-to-gas ratio, the coefficient $x$ means the dust optical depth for LC photons itself. We find in Paper I that $x \approx 2$ for the observed LC photon production rates and electron number densities in the sample of Galactic H II regions. Petrovian et al. (1972) have derived the relation between the monochromatic dust optical depth, $\tau_d$, and $f$:

$$f = \frac{x^3_d}{3[e^{x_d}(x_d^2 - 2x_d + 2) - 2]}. \quad (6)$$

This relation is shown in Figure 1 of Paper I. When $D$ is given, therefore, we determine $f$ via equations (5) and (6). The data points in Figure 3 are well reproduced by setting $x \approx 1$–2 in equation (5).

Here we assume that the dust-to-gas ratio in H II regions is almost equal to a typical value of that in the ISM of the host galaxy, although the ratio locally may vary significantly across the galaxy (Stanimirovic et al. 2000). On the other hand, the mean value of the dust-to-gas ratio of the H II gas in our Galaxy is almost equal to those of the H I and H$_2$ gas (Sodroski et al. 1997). Thus, the assumption may be valid globally.

In this paper, the determined $f$ values are systematically somewhat larger than those in Paper I. That is, the suitable $x$ coefficient in equation (5) for the data points is 1 rather than 2, which is the best-fit value in Paper I. This may be because we neglect the MIR component emitted by very small grains and PAHs in the dust IR luminosity (see § 2). Thus, $f$ determined here may be an upper limit. Also, $f$ in Paper I is considered a lower limit because the scattering of LC photons by dust is not taken into account in Paper I.

Anyway, the model presented by equations (5) and (6) can reproduce the trend of the observational data, when the coefficient $x$ is set to between 1 and 2. In short, the $D$-$f$ relation falls in the area between the two curves in Figure 3. Therefore, we conclude that $f$ is expected to be a function of dust-to-gas ratio (or metallicity): as the dust content increases, $f$ becomes smaller.

### 4.2. Effect of LCE on Estimating SFR

Finally we discuss the effect of the LCE on estimating the SFR. By the definition of $f$ in equation (1), we obtain the
Figure 4—Correction factor, using the LCE effect, for the star formation rate as a function of the dust-to-gas ratio. The correction factor is $1/f$. The top and bottom curves show the case for $x = 1$ and 2, respectively, in eq. (5). The correction factor is expected in the shaded area between two curves.

correction factor, by using the LCE, for the SFR as $1/f$. If $f$ is a function of the dust-to-gas ratio, the correction factor is also a function of the dust-to-gas ratio. This is shown in Figure 4.

Clearly, we find that the correction factor increases as the dust-to-gas ratio increases. For nearby spiral galaxies, their dust-to-gas ratios are distributed around the Galactic value (Alton et al. 1998; Stickel et al. 2000; see also Paper I). Indeed, even the starburst galaxies (e.g., M82) and the ultraluminous IR galaxies (e.g., Arp 220) are likely to be distributed about the Galactic dust-to-gas ratio (Krügel, Steppe, & Chini 1990; Lisenfeld, Isaak, & Hills 2000). For such a dust-to-gas ratio, we expect that the correction factor is 2–5. Thus, the effect of the LCE is more important than the uncertainty of the initial mass function, which is about a factor of 2 (e.g., Inoue et al. 2000). Therefore, we should take account of the LCE effect when we estimate the SFR of nearby spiral galaxies.

5. CONCLUSIONS

To examine the Lyman continuum extinction (LCE) in H II regions, we compared the observed infrared emission with the production rate of Lyman continuum photons for 49 H II regions in our Galaxy, M31, M33, and the LMC. Then we estimate the fraction, $f$, of Lyman continuum photons contributing to hydrogen ionization in these regions. We reached the following conclusions:

1. In many H II regions, $f$ is smaller than 0.5. The mean $f$ of the sample regions in spiral galaxies (our Galaxy, M31, and M33) is about 0.4. On the other hand, the mean $f$ in the H II regions in the LMC is about 0.7.

2. The mean $f$ of sample H II regions in each galaxy may be a function of metallicity or the dust-to-gas ratio of their host galaxy; that is, $f$ decreases as the metallicity or dust-to-gas ratio increases.

3. The observational trend is reproduced very well by the model in which the dust optical depth for Lyman continuum photons over the ionized region is proportional to the dust-to-gas ratio. The dust optical depth is between 1 and 2 for the Galactic dust-to-gas ratio.

4. It is expected that the correction factor for the star formation rate by the LCE increases as the dust-to-gas ratio (metallicity) increases. The expected correction factor for the galaxies with the Galactic dust-to-gas ratio is 2–5. Therefore, the LCE effect should be taken into account when we estimate the SFR of the nearby spiral galaxies, since the dust-to-gas ratios of these galaxies are almost same as that in the Galaxy.

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APPENDIX A

INFRARED EXCESS

The IR excess (IRE) is often examined for H II regions. We examine the relation between the LCE and IRE. Especially, we relate $f$ to IRE directly here. A related discussion is found in Hirashita et al. (2001). Mezger et al. (1974) have defined the IRE as

$$\text{IRE} \equiv \frac{L_{\text{IR}}}{N_{\text{LC}} \hbar \nu_{\text{Ly}\alpha}},$$

where $h$ is Planck's constant and $\nu_{\text{Ly}\alpha}$ denotes the frequency at the Lyman $\alpha$ line. From equation (A1) we obtain $L_{\text{IR,7}} / N_{\text{LC,50}} = 4.23 \times 10^{-2}\text{IRE}$. Therefore, equation (2) is

Figure 5.—Fraction of Lyman continuum photons contributing to hydrogen ionization, $f$, as a function of infrared excess, IRE. The solid, dotted, dashed, and dash-dotted lines are calculated by using eq. (A2) with $\epsilon = 1.0$, 0.7, 0.4, and 0, respectively.
reduced to

\[
f = \frac{0.44 + 0.56e}{0.28 + 0.241 \text{IRE}}.
\]  

(A2)

In Figure 5, we show the relation between \( f \) and \( \text{IRE} \) derived from equation (A2) for various \( e \).

The solid, dotted, and dashed lines correspond to \( e = 1.0 \) (in the Galaxy), 0.7 (in M31 and M33), and 0.4 (in LMC), respectively. In addition, we also present for comparison the dash-dotted line, \( e = 0 \), corresponding to the case in which no nonionizing photons are absorbed by dust. According to Spitzer (1978), the probability of producing Lyman \( \alpha \) photons is 2/3 per every ionization-recombination process of hydrogen. Thus, when the observed IR luminosity of an H II region is explained only by the luminosity of Lyman \( \alpha \) photons produced in the region (\( f = 1 \) and \( e = 0 \)), \( \text{IRE} \) will be 0.67.

Antonopoulou & Pottasch (1987) have reported 4 < \( \text{IRE} < 40 \) for the Galactic compact H II regions. The mean \( \text{IRE} \) of their sample is about 12. For such high IRE regions, we expect that \( f \) is about 0.3 or less. When we estimate the SFR of such regions, therefore, we should not use the Hz or thermal radio luminosities but use the IR luminosity as an indicator of the SFR.

REFERENCES

Aannestad, P. A. 1989, ApJ, 338, 162
Alton, P. B., et al. 1998, A&A, 338, 807
Antonopoulou, E., & Pottasch, S. R. 1987, A&A, 173, 108
Aumann, H. H., Fowler, J. W., & Melnyk, M. 1990, AJ, 99, 1674
Bottorff, M., LaMothe, J., Momjian, E., Verner, E., Vinković, D., & Ferland, G. 1998, PASP, 110, 1040
Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582
Caplan, J., Deharveng, L., Peña, M., Costero, R., & Blondel, C. 2000, PASJ, 52, 539
Condon, J. J. 1992, ARA&A, 30, 575
Cram, T. R., Roberts, M. S., & Whitehurst, R. N. 1980, A&AS, 40, 215
DeCia, D., M., & Steppe, H., & Chini, R. 1990, A&A, 229, 17
Duric, H., Viallefond, F., Goss, W. M., & van der Hulst, J. M. 1993, A&AS, 99, 217
Dwek, E., et al. 1997, ApJ, 475, 565
Förster, E., Reich, W., & Sofue, Y. 1987, A&AS, 71, 63
Gordon, K. D., Clayton, G. C., Witt, A. D., & Missett, K. A. 2000, ApJ, 533, 236
Haas, M., Lemke, D., Stickel, M., Hippelein, H., Kunkel, M., Herbstmeier, U., & Mattila, K. 1998, A&A, 338, L33
Harper, D. A., & Low, F. J. 1971, ApJ, 165, L9
Hirashita, H., Inoue, A. K., Kamaya, H., & Shibai, H. 2001, A&A, 366, 83
Howarth, I. D. 1983, MNRAS, 203, 301
Inoue, A. K., Hirashita, H., & Kamaya, H. 2000, PASJ, 52, 539
———. 2001a, ApJ, 555, 613 (Paper I)
———. 2001b, in ASP Conf. Ser. 222, The Physics of Galaxy Formation, ed. M. Umemura & H. Susa (San Francisco: ASP), 329
Ishida, K., & Kawajiri, K. 1968, PASJ, 20, 95
Issa, M. R., MacLaren, I., & Wolfendale, A. W. 1990, A&A, 236, 237
Kessler, M. F., et al. 1996, A&A, 315, L27
Kroes, H., Steppe, H., & Chini, R. 1990, A&A, 229, 17
Leitherer, C., Ferguson, H. C., Heckman, T. M., & Lowenthal, J. D. 1995, ApJ, 454, L19
Lillie, C. F., & Witt, A. N. 1976, ApJ, 208, 64
Lisenfeld, U., Isaak, K. G., & Hills, R. 2000, MNRAS, 312, 433
Mahtara, T., Oda, N., & Okuda, H. 1979, ApJ, 227, L129
Mathis, J. S. 1971, ApJ, 167, 261
Mezger, P. G., Smith, L. F., & Churchwell, E. 1974, A&A, 32, 269
Natta, A., & Panagia, N. 1976, A&A, 50, 191
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: University Science Books)
Panagia, N. 1974, ApJ, 192, 221
Petrosian, V., Silk, J., & Field, G. B. 1972, ApJ, 177, L69
Pišmiš, P., & Mampaso, A. 1991, MNRAS, 249, 385
Rice, W. 1993, AJ, 105, 67
Sarazin, C. L. 1977, ApJ, 211, 772
Savage, B. D., & Mathis, J. S. 1979, ARA&A, 17, 73
Seaton, M. J. 1979, MNRAS, 187, 73
Shields, J. C., & Kennicutt, R. C. 1995, ApJ, 454, 807
Smith, L. F., Biermann, P., & Mezger, P. G. 1978, A&A, 66, 65
Sodroski, T. J., Odegard, N., Arendt, R. G., Dwek, E., Weiland, J. L., Mauger, M. G., & Kelsall, T. 1997, ApJ, 480, 173
Spitzer, L. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)
Stanimirovic, S., Staveley-Smith, L., van der Hulst, J. M., Bottemoe, Tj., Kester, D. M., & Jones, P. A. 2000, MNRAS, 315, 791
Stickel, M., et al. 2000, A&A, 359, 865
van den Bergh, S. 2000, The Galaxies of the Local Group (Cambridge: Cambridge Univ. Press)
Walterbos, R. A. M., & Braun, R. 1992, A&A, 236, 625
Witt, A. N., & Lillie, C. F. 1973, A&A, 25, 237
Wynn-Williams, C. G., & Becklin, E. E. 1974, PASP, 86, 5
Xu, C., & Helou, G. 1996, ApJ, 456, 152
Xu, C., Klein, U., Meinert, D., Wielebinski, R., & Haynes, R. F. 1992, A&A, 257, 47

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