SPATIAL DISTRIBUTION OF DUST GRAINS WITHIN H II REGIONS

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ABSTRACT

We discuss the dust distribution within photoionized regions. Assuming a geometry with a central dust cavity, which is strongly suggested by the literature, we can estimate the cavity’s radius from the ratio of the infrared and radio fluxes by using a simple transfer model of Lyman continuum photons. We apply the method to a sample of the Galactic H II regions. The estimated typical radius of the dust cavity of the Galactic compact H II regions is about 30% of the Strömgren radius. Taking account of uncertainties both of the observational data and the model, we can reject a dust distribution lacking a central cavity. Therefore, the dust cavity model is supported independently of the previous works. We discuss the formation mechanism of such a dust cavity and its detectability by present and future infrared facilities.

Subject headings: dust, extinction — H II regions — infrared: ISM — radiative transfer — submillimeter

1. INTRODUCTION

Dust grains exist everywhere. The inside of H II regions is not an exception (e.g., Ishida & Kawajiri 1968; Harper & Low 1971; Melnick 1979). The radiation from celestial objects is always absorbed and scattered by the grains. Without 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 misled. In order to evaluate the amount of the dust extinction in detail, it is important to know the distribution of dust as well as its optical properties.

Theoretically, some attempts to reveal the dust distribution in H II regions have been made to date (Mathews 1967, 1969; Gail & Sedlmayr 1979a,b). According to Gail & Sedlmayr (1979b), the radiation pressure on the dust grains by the central source causes a central hole of dust and gas. The dust distribution has also been observationally investigated. From the observed flux ratio of H β to continuum, O’Dell & Hubbard (1965) have shown that the gas-dust ratio decreases with radius in the Orion nebula. From radial photometric profiles at V-band of some H II regions, Nakano et al. (1983) also suggest that a dust depletion zone is in the central region (See also Yoshida et al. 1986, 1987). Moreover, the central dust cavity is supported by fitting to the observed infrared (IR) spectral energy distribution (SED) of H II regions (Chini, Krügel, & Kreyssy 1986; Chini, Krügel, & Wargau 1987; Churchwell, Wolfire, & Wood 1990; Faison et al. 1998; Ghosh et al. 2000). Recently, such dust geometry is preferred not only by IR SED fitting but also by the radial photometric profiles at submillimeter range (Hatchell et al. 2000). In addition, we have some evidence of central gaseous cavities from radio observations (Terzian 1965; Wood & Churchwell 1989). Since dust and gas are well coupled each other (Gail & Sedlmayr 1979b), the presence of a gaseous cavity indicates a dust cavity.

Although the dust cavity is likely to exist, it has not been observed directly in the far-infrared (FIR) band, which is dominated by the thermal emission from dust. This is because the FIR observations are not advanced relative to other wavelengths, and moreover, the spatial resolving power of FIR imaging is generally weak. Recently, more detailed observational data have been obtained by ISO (Infrared Space Observatory) and SCUBA (Submillimeter Common-User Bolometer Array), and many successive facilities are planned in the near future (SIRTF, SOFIA, ASTRO-F, ALMA, etc.). By using these new powerful facilities, we may observe the dust distribution directly. We need to estimate the detectability of the cavity by these facilities.

On the other hand, we have developed a method for determining the fraction of Lyman continuum (LC) photons contributing to hydrogen ionization (Inoue, Hirashita, & Kamaya 2001; Inoue 2001, hereafter Paper I and Paper II, respectively). In paper I and II, we show that only half of LC photons from the central source in an H II region ionizes neutral hydrogens, and the rest are absorbed by dust grains within the ionized region. If a dust cavity exists in the ionized region, however, the efficiency of the dust absorption for the LC photons becomes small. In this paper, we examine whether the estimated photon fraction is reproduced by a model nebula with a central dust cavity.

In the next section, we describe our method for examining the dust distribution, especially the central dust cavity’s radius, by using the fraction of LC photons contributing to hydrogen ionization. In section 3, we apply it to the sample H II regions in the Galaxy. Then, we discuss the formation mechanism of the dust cavity and its detectability by some IR facilities in section 4. Finally, we summarize our conclusions in the last section.

2. METHOD

2.1. Photon Transfer

We assume an ideal spherical nebula composed of only hydrogen and dust because the effect of helium is not so important for the determination of the dust distribution. This will be discussed in more detail in the last paragraph.
of section 2.3.2. Moreover, we assume the volume number densities of hydrogen and dust to be constant, $n_{\text{H}}$ and $n_d$, respectively. If densities of neutral hydrogen atoms, protons, and electrons, are represented by $n_{\text{H}0}$, $n_p$, and $n_e$, respectively, we have $n_{\text{H}0} = (1 - x)n_{\text{H}}$ and $n_p = n_e = xn_{\text{H}}$ in terms of the ionization degree, $x$, which varies with the radius, $r$, from the central exciting source. In addition, we assume the frequencies of all LC photons to be that of the Lyman limit, that is, all quantities are treated monochromatically in our transfer model. This is because we obtain only the number of LC photons from observations of recombination lines or thermal radio emissions from H II regions.

We introduce a dimensionless radius, $y = r/R_S$, where $R_S$ is the classical Str"omgren radius which is defined as

$$R_S = \left( \frac{3N_{\text{LC}}}{4\pi n_{\text{H}}^2 \alpha B} \right)^{1/3}. \tag{1}$$

Here $N_{\text{LC}}$ is the intrinsic production rate of LC photons of the central source, and $\alpha_B$ is the Case B recombination coefficient of hydrogen.

We consider the change of the number of LC photons passing through the shell whose inner and outer radii are $y$ and $y + dy$, respectively. If the number of LC photons entering the shell per unit time denotes $N_{\text{LC}}(y)$, its change in the shell is

$$dN_{\text{LC}}(y) = -N_{\text{LC}}(y)\left\{n_{\text{H}0}s_{\text{H}} + (1 - \omega)n_ds_d\right\}R_S dy + 4\pi R_S^3 y^2 n_p n_e \alpha_1 dy, \tag{2}$$

where $s_{\text{H}}$ and $s_d$ are cross sections for LC photons of neutral hydrogen atoms and dust grains, respectively, $\omega$ is the dust albedo for these photons, and $\alpha_1$ is the recombination coefficient to the ground state of hydrogen. We neglect the asymmetric effect of the dust scattering for simplicity.

Since the shell is in ionization equilibrium,

$$N_{\text{LC}}(y)n_{\text{H}0}s_{\text{H}}R_S dy = 4\pi R_S^3 y^2 n_p n_e \alpha_A dy, \tag{3}$$

where $\alpha_A$ is the coefficient of hydrogen recombination to all levels. We note that $\alpha_A = -\alpha_B = \alpha_1$. By equation (3) and replacing $n_{\text{H}0}$ with $(1 - x)n_{\text{H}}$, equation (2) is reduced to

$$dN_{\text{LC}}(y) = -N_{\text{LC}}(y)\left\{(1 - x)\frac{\alpha_B}{\alpha_A} + X\right\}n_{\text{H}}s_{\text{H}}R_S dy, \tag{4}$$

where

$$X = (1 - \omega)\frac{n_ds_d}{n_{\text{H}}s_{\text{H}}}. \tag{5}$$

This is a correction term for existence of dust grains in the nebula. If we define the total (gas + dust) optical depth for LC photons as

$$d\tau = \left\{(1 - x)\frac{\alpha_B}{\alpha_A} + X\right\}n_{\text{H}}s_{\text{H}}R_S dy, \tag{6}$$

we obtain $N_{\text{LC}}(y) = N_{\text{LC}} e^{-\tau}$. Then equation (3) is reduced to

$$1 - x = \frac{4\pi R_S^2 y^2 n_{\text{H}} \alpha_A}{s_{\text{H}} N_{\text{LC}} e^{-\tau}}. \tag{7}$$

Now we define the ionization parameter as

$$U = \frac{N_{\text{LC}}}{4\pi R_S^2 n_{\text{H}} c} = \frac{1}{c} \left( \frac{\alpha_B^2 n_{\text{H}} N_{\text{LC}}}{36\pi} \right)^{1/3}, \tag{8}$$

where $c$ is the light speed. Then equations (6) and (7) are reduced to

$$\frac{d\tau}{dy} = \frac{3c s_{\text{H}}}{\alpha_B} \left\{(1 - x)\frac{\alpha_B}{\alpha_A} + X\right\} U, \tag{9}$$

and

$$1 - x = \frac{\alpha_B y^2 e^x}{s_{\text{H}} c U}, \tag{10}$$

respectively.

Finally, we determine two recombination coefficients of hydrogen, $\alpha_A$ and $\alpha_B$. The coefficients are a function of the electron temperature, $T_e$ (Spitzer 1978). Fitting values in Table 5.2 of Spitzer (1978), we can approximate them to the following equation;

$$\frac{\alpha_i}{\text{cm}^3\text{s}^{-1}} = 2.06 \times 10^{-11} a_i - \log T_e/4000 \text{K}, \tag{11}$$

for $2000 \text{K} \lesssim T_e \lesssim 16000 \text{K}$, where $i = A$ or $B$, and $a_A = 2.40$ and $a_B = 1.64$. The uncertainties of values determined by these equation are less than 1% for the above range of $T_e$.

2.2. Dust Properties

Let us estimate the dust effect that appears in the term, $X$. We adopt the dust extinction law in the Galactic interstellar medium (ISM) developed by Weingartner & Draine (2001), who have derived a size-distribution function of dust grains composed of carbonaceous and silicate populations by Draine & Lee (1984) and Li & Draine (2001). Their carbonaceous grain includes PAH (polycyclic aromatic hydrocarbon) molecules. Weingartner & Draine (2001) have developed the extinction laws for various values of $R_V$, which is the ratio of the visual extinction to color excess.

We approximate the optical depths for LC photons by hydrogen and dust to those at 912 Å. According to Weingartner & Draine (2001), the dust cross sections per unit hydrogen nucleus at 912 Å i.e. $n_d s_{\text{H}12}^9/\text{n}_\text{H}$ are $2.515 \times 10^{-21} \text{cm}^2$, $1.676 \times 10^{-21} \text{cm}^2$, and $1.087 \times 10^{-21} \text{cm}^2$, for $R_V = 3.1, 4.0$, and 5.5, respectively. We note that these values are calibrated by $A_I/\text{n}_\text{H} = 2.6 \times 10^{-22} \text{cm}^2$, where $N_H$ is the hydrogen column density. Also, the gas albedos at 912 Å are 0.2451, 0.2694, and 0.2989 for $R_V = 3.1, 4.0$, and 5.5, respectively. If we adopt $s_{\text{H}12}^9 = 6.3 \times 10^{-18} \text{cm}^2$, equation (5) is reduced to

$$X = \begin{cases} 3.0 \times 10^{-4} & \text{for } R_V = 3.1 \\ 1.9 \times 10^{-4} & \text{for } R_V = 4.0 \\ 1.2 \times 10^{-4} & \text{for } R_V = 5.5 \end{cases}. \tag{12}$$

Here, we introduce a parameter for the dust distribution, the dimensionless dust cavity’s radius, $y_d$, because the dust distribution may have a radial dependence as strongly suggested in the literature (§1). For simplicity, we consider an extreme case that no dust is inside the cavity’s radius, $y_d$, and the gas-dust ratio is constant outside of it. That is, the dust term, $X$, is zero within $y_d$, and constant value shown above outside of it.

Now, we can solve the photon transfer problem. If the ionization parameter, $U$, is given, and $\tau = 0$ and $x = 1$ at

1 We adopt the extinction laws with the parameter sets recommended by Weingartner & Draine (2001). For $R_V = 3.1$, we adopt the law with the parameter set of Case A and $b_5 = 6.0 \times 10^{-5}$, which represents C abundance of very small grain population. Also, we adopt the laws with the parameter sets of Case B and $b_5 = 4.0 \times 10^{-5}$, or Case B and $b_5 = 3.0 \times 10^{-5}$ for $R_V = 4.0$, or 5.5, respectively. Values of other parameters are tabulated in Table 1 in Weingartner & Draine (2001).
y = 0 are adopted as the boundary condition, we obtain the ionization degree, x, at any radius, y, from equations (9) and (10) for a set of $R_V$ and $T_e$. The dust inner radius, $y_d$, is only one free parameter in our photon transfer model.

2.3. Ionizing Photon Fraction

As investigated in Paper I and II, not all of the intrinsic LC photons emitted by the central source of H II regions is consumed in hydrogen ionization. In other words, the number of LC photons contributing to the ionization, i.e., ionizing photons, is always less than the intrinsic one. Then, we define the ionizing photon fraction, $f$, as

$$f = \frac{N'_{LC}}{N_{LC}}$$

where $N'_{LC}$ and $N_{LC}$ are the production rates of the ionizing and intrinsic LC photons, respectively. For the ionizing photons, the production rate, $N'_{LC}$, is determined from the observational data, whereas the intrinsic production rate, $N_{LC}$, cannot be obtained observationally. Let us determine the fraction, $f$, via two ways below.

2.3.1. From Transfer Model

First, we determine the fraction from our transfer model. According to Paper I, the fraction, $f$, is reduced to $y^3_i$ for a perfectly ionized nebula (i.e., $x = 1$ for $y < y_i$ and $x = 0$ for $y > y_i$), where $y_i$ is the dimensionless radius of the ionized region.

Total number of proton in a nebula is $\int x n_H 4\pi R^2 y^2 dy$ in our transfer model. On the other hand, the proton number is equal to $(4\pi/3)R^3 y^2 n_H$ in the perfectly ionized nebula. Since our solutions of the photon transfer model indicate that the nebula is regarded as the perfectly ionized nebula, we can equate above two quantities each other. Thus, we obtain

$$f = 3 \int_{y_0}^{y_{\text{max}}} x y^2 dy,$$

where $y_{\text{max}}$ is the position to stop calculating. We can choose the value of $y_{\text{max}}$ arbitrarily if it is larger than $y_i$. In this paper, $y_{\text{max}} = 1$ is adopted as a constant for simplicity. Therefore, we can determine $f$ as a function of the dust inner radius, $y_d$, for three $R_V$ values, if an ionization parameter, $U$, is given. We note that the fraction determined from above equation (14) becomes equivalent to that in section 2 of Paper I if $y_d = 0$ and $\omega = 0$.

In Figure 1, we show such results for various sets of $U$ and $R_V$ when we adopt $T_e = 6600$ K which is a mean electron temperature of the sample H II regions described in section 3. We find that $f$ decreases if $y_d$ decreases. This is because the dust optical depth is large as the cavity’s radius is small. We also find that $f$ decreases if $U$ increases, which is equivalent that $f$ decreases if $N_{LC}$ or $n_H$ increases (eq.[8]). This indicates that the ionizing photon fraction for a dust-gas ratio\(^2\) becomes smaller as the number of LC photons from the central source becomes larger or as the density of the surrounding medium becomes higher.

\(^2\) In this paper, we adopt a dust-gas ratio corresponding to $A_V/N_H = 2.6 \times 10^{-22}$ cm\(^2\) (see section 2.2). Since the dust-gas ratios are different from one region to others (e.g., Stanimirovic et al. 2000 for the SMC), we should determine the ratio for the individual H II region. However, we use the above dust-gas ratio for all sample regions, because we cannot determine it individually.

The relation between $f$ and $y_d$ is also a function of $R_V$, as shown especially in Figure 2 (a). That is, the ionizing photon fraction for a fixed dust cavity’s radius becomes smaller, as the value of $R_V$ becomes smaller. This is because the dust extinction law of a smaller $R_V$ shows a steeper rise at the far-ultraviolet range (Weingartner & Draine 2001). Since a higher value of $R_V$ is suitable for a higher density region (Cardelli, Clayton, & Mathis 1989), we select $R_V = 5.5$ for our sample H II regions discussed in section 3. Moreover, we see the variation of the $f$-$y_d$ relation for the change of the adopted electron temperature, $T_e$. We find in Figure 2 (b) that $f$ becomes smaller as $T_e$ becomes higher, because recombination coefficients becomes larger as $T_e$ increases.

2.3.2. From Observational data

Next, we determine the ionizing photon fraction, $f$, from the observational data. According to Paper I and II, we can estimate $f$ from the ratio of the IR luminosity, $L_{IR}$, to the ionizing photon production rate, $N_{LC}$, (equation [2] in Paper II) unless a significant amount of LC photons escapes from H II regions.\(^3\) However, in the derivation in Paper II, the stellar SED are assumed to be the Planck function. Thus, we overestimate the intrinsic production rate of LC photons, and then, we underestimate $f$ in Paper II.

In this paper, we adopt a realistic stellar spectra, the Kurucz’s ATLAS 9 spectra with solar abundance and turbulence speed of 2 km s\(^{-1}\). Then, if a Salpeter’s IMF (0.1–100 $M_\odot$) is assumed, we derive the following formula:

$$f = \frac{0.375 + 0.625\epsilon}{0.250 + 4.42L_{IR,6}/N'_{LC,49}},$$

where $\epsilon$ denotes the average efficiency of dust absorption for nonionizing UV ($\lambda > 912$ Å) photons, and $L_{IR,6}$ and $N'_{LC,49}$ are the total IR luminosity and ionizing photon production rate normalized by $10^6 L_\odot$ and $10^{49}$ s\(^{-1}\), respectively. The value of $f$ obtained from the above equation is typically 1.2 times larger than that from the equation (2) in Paper II because of the modification of adopted stellar SED. When we estimate $\epsilon$ from the observed color excess (see Paper II for detail), we determine $f$ of individual H II region from its $L_{IR}$ and $N'_{LC}$. It is worthwhile to note that since the above equation is based on a simple energy conservation, the obtained $f$ is independent of the dust distribution, the structure of H II regions and so on.

Once $f$ is obtained, we can determine the intrinsic LC photon production rate by using equation (13), and can determine the ionization parameter, $U$. Using the obtained $U$, we determine $y_d$ so as to reproduce $f$ determined from equation (15) by using our photon transfer model (i.e. eq.[14]). In the next section, we determine a typical $y_d$ for a sample of the Galactic H II regions.

We discuss the effect of the presence of helium. Of course, helium atoms absorb LC photons as well as hydrogen and dust. However, the fraction of stellar LC photons ionizing helium is small, $\lesssim 10\%$. Even if all helium ionizing photons are consumed by only helium, the fraction of photons ionizing hydrogen, $f$, becomes at most 10%.

\(^3\) For details of the derivation, see also Inoue, Hirashita, & Kamaya (2000).
smaller than that determined by equation (15). Thus, the determined $y_d$ decreases at most 10%. Since not all helium ionizing photons are absorbed by helium and most of helium recombination photons can ionize hydrogen (Mathis 1971), the effect of helium is negligible for our analysis.

3. RESULTS

In order to determine the inner radius of the dust distribution, $y_d$ of an H II region, we need various data; the electron density and temperature, the ionizing photon production rate, the infrared luminosity, and $R_V$. Here, the value of $R_V$ is assumed to be constant, 5.5. The effect of the change of $R_V$ is discussed quantitatively in the last part of this section.

We find a suitable data set of the Galactic H II regions in Simpson et al. (1995), which examined the physical properties of 23 H II regions in the Galaxy observed by the Kuiper Airborne Observatory. We select 13 H II regions from the sample of Simpson et al. (1995). The adopted selection criterion is that the measured electron number density exceeds 1000 cm$^{-3}$. The selected regions are classified into the 'compact' or 'ultra-compact' H II regions from their densities (Habing & Israel 1979). The spherical geometry of our transfer model may be not so bad for such sample, although even the 'ultra-compact' H II regions sometimes show non-spherical shapes (Wood & Churchwell 1989). For more evolving H II regions than the 'compact' class, which often show very complex shapes, e.g., 'blister', 'bubble', 'champagne', etc., the spherical assumption is not valid. The observed and measured quantities of the sample regions are tabulated in Table 1.

First, we estimate the ionizing photon fraction, $f$, for each sample region. The ionizing photon production rate, $N_{\text{LC}}$, is estimated from the flux density of free-free radio emission at 5 GHz by the formula in Condon (1992): $N_{\text{LC}}^{1/2}/\text{s}^{-1} = 8.88 \times 10^{46} (T_e/10^4\text{K})^{-0.45} (\nu/5\text{GHz})^{0.1} (D/\text{kpc})^2 (S_{\nu}/\text{Jy})$. The total IR (8–1000 μm) luminosity, $L_{\text{IR}}$, is estimated from the observed IR (18–160 μm) flux by an upward factor of 1.26, assuming the dust SED to be the modified Planck function of 30 K with the emissivity index of 1. The conversion factor varies between 1.03–1.26 if we change the adopted parameter sets of the dust temperature (30–40 K) and the emissivity index (1–2). Thus, the conversion causes at most 20% uncertainty of the derived IR luminosity. The determined $N_{\text{LC}}$ and $L_{\text{IR}}$ are given in columns (2) and (3) of Table 2, respectively.

Since we do not have the color excess, $E_{B-V}$, of sample regions, we assume $c = 1$, which correspond to a typical $E_{B-V}$ of the Galactic H II regions observed by Caplan et al. (2000) (See Paper II). The determined $f$ may be overestimated if the true value of $c$ is smaller than unity. Indeed, if we set $c = 0.8$, the value of $f$ becomes about 90% of the determined here. Now, we can determine $f$ for each sample region via equation (15), and give the values in column (4) of Table 2. The mean value and standard deviation of $f$ for 13 sample regions are 0.55 and 0.22, respectively. Thus, only half of LC photons contribute to hydrogen ionization in the H II regions of the Galaxy. This is consistent with the results in Aannestad (1978), Paper I and II.

Since the ionizing photon fraction, $f$, is indirect measurement value, many uncertainties of adopted quantities accumulate. Suppose a quantity, $\eta$, is represented by a functional form, $\phi(x_1, x_2, ...)$, where $x_i$ is a more basic quantity. If uncertainties of $x_i$ are represented by $\delta_i$, and all quantities of $x_i$ are independent each other, the uncertainty of $\eta$ can be expressed by $\sum (\partial \eta / \partial x_i)^2 \delta_i$. In this way, the uncertainty of $L_{\text{IR}}/N_{\text{LC}}^{1/2}$ is estimated to be about 30% typically. The main causes of the uncertainty are that of the adopted radio flux densities, about 20% (Simpson et al. 1995). Taking account of the uncertainties of the coefficients in equation (15) and the parameter, $c$, we estimate a typical uncertainty of $f$ to be about 33%, which corresponds to ±0.2 for the mean $f$. Thus, a somewhat large value of $f$ for G298.22-0.34, in stead of $f \leq 1$ by the definition, may be caused by this uncertainty.

Next, we determine the dust cavity’s radius, $y_d$, of sample regions. By using the estimated $f$, we can convert the ionizing photon production rate, $N_{\text{LC}}$, into the intrinsic LC one, $N_{\text{LC}}^{1/2}$, that is, $N_{\text{LC}} = (f \mu \eta) N_{\text{LC}}^{1/2}$. Then, we calculate the ionization parameter, $U$, of the individual sample region by equation (8) shown in column (5) in Table 2. Here, we determine $y_d$ so that $f$ estimated from equation (15) is equal to $f$ calculated from our transfer model (i.e., eq. [14]).$^4$ The obtained values of $y_d$ are given in the last column in Table 2. The mean value of the determined $y_d$ and its standard deviation are 0.39 and 0.23, respectively. The uncertainty of the individual value of $y_d$ caused by that of the estimated $f$ is about ±0.2.

In Figure 3, we show histograms of the derived quantities. From the panels (c) and (d), we can divide the sample into two groups: one is the 'ultra-compact' H II regions, whose Strömgren radius, (or the ionized radius, $r_1$) is smaller than 0.5 pc (0.4 pc). The other is the 'compact' H II regions with more larger radii. Here, we should note that G298.22-0.34 is removed from the following discussions because of its anomalous value of $f$, and S156 is also removed because of its very small luminosity relative to others. The two classifications are indicated in Figure 3 and Table 1. In Table 3, we summarize the mean properties of the sample of the two groups. Although our classification is based on the radius of sample regions, the classification is caused by the difference of the electron density, and are consistent with that of Habing & Israel (1979).

For the 'compact' sample, we estimate the mean value of $y_d$ to be 0.30 ± 0.12, where the error is the sum of two uncertainties of the mean value; one results from the variation among sample regions, and the other from the uncertainty of individual value. The estimated error is coincident with the sample standard deviation. For the 'ultra-compact' sample, the mean value of $y_d$ is estimated to be 0.48 ± 0.26. The error is the same mean as that of the 'compact' sample.

The non-zero mean value of $y_d$ obtained above may results from a somewhat large uncertainty of individual object. If we assume that the sample regions compose a normal population, we can test whether the mean $y_d$ of the population is regarded to be zero. If the variance of $y_d$ for the population is estimated to be square of the uncertainty of individual value, $(0.2)^2$, we can reject the hypothesis of

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$^4$ Determining $y_d$, we adopt the recombination coefficients calculated from the individual electron temperature by equation (11).
the mean \( y_d = 0 \) with the significance level of 0.0011% for
the 'compact' sample, and 0.0016% for the 'ultra-compact'
sample. Therefore, even if we take account of somewhat
large uncertainties of the observations and the model, the
ionizing photon fraction cannot be reproduced by a nebula
filled with dust uniformly (i.e. \( y_d = 0 \)). The dust distribution
with the central cavity is supported by our analysis
independently of the IR SED fitting or the photometric
profile analysis.

The cavity's radius in units of the Strömgren radius (i.e.
\( y_d \)) of the 'ultra-compact' sample is larger than that of the
'compact' sample. The real scale of the cavity's radii of
both samples are about 0.3 pc and 0.2 pc for 'compact'
and 'ultra-compact', respectively. We may see an evolu-
tionary sequence of the dust cavity from 'ultra-compact'
 to 'compact'. However, these values are agree with each other
within their error bars, and the 'ultra-compact' sam-
ple consists of only three regions. Thus, it is uncertain
whether the difference between the cavity's radii of two
subsamples is real or not.

Finally, we demonstrate the effect of the change of \( R_V \)
on the obtained dust cavity's radius, \( y_d \). As shown in Fig-
ure 2 (a), the value of \( y_d \) increases for a fixed ionizing
photon fraction, \( f \), if \( R_V \) decreases. This is shown quanti-
tatively for three sample set in Table 4. For the 'compact'
sample, the value of \( y_d \) of \( R_V = 3.1 \) is a factor of 1.7 times
larger than that of \( R_V = 5.5 \).

4. DISCUSSIONS

As described above, assuming spherical symmetry and
uniform density distribution, we obtain a typical radius
of the central dust cavity in the 'compact' \( \text{H II} \) regions,
0.3 times Strömgren radius. This corresponds about 40
% of the ionized radius and about 0.3 pc. We discuss
the formation mechanism and the detectability of the cavi-
ity. However, we should keep in mind that since real \( \text{H II} \)
regions, even compact or ultra-compact regions, show a complex structure, the radius of a real cavity may be
different from 0.3 pc obtained by our model.

4.1. Formation Mechanism

Three formation mechanisms of the central dust cavity
are naturally expected: (1) radiation pressure, (2) stellar
wind by the central source, and (3) dust sublimation. Here
we discuss whether the above mechanisms can produce the
cavity and which is more effective.

The effect of radiation pressure of the central source on
the distribution of gas and dust in \( \text{H II} \) regions is discussed
in detail by Gail & Sedlmayr (1979b). According to them,
the radiation force acting on the dust grain produces the
central cavity of dust and gas (See their Fig.7). The radius
of the cavity is about 20% of the ionized radius. Although
we cannot directly compare their cavity's radius with that
in this paper because of the difference between the adopted
parameter sets, the radiation pressure can produce a large
cavity.

Also, strong stellar wind of the massive stars must con-
tribute to produce the central cavity. Indeed, the central
low density cavity of gas is produced by the stellar wind
(e.g., Comerón 1997). Since dust and gas are well coupled
with each other (Gail & Sedlmayr 1979b), the gas cavity
indicates the dust cavity. Unfortunately, we cannot esti-
mate quantitatively the contribution of the stellar wind to
form the dust cavity here. It is beyond the scope of this
paper. We will resolve which of radiation pressure and
stellar wind is dominant mechanism to form the cavity in
our future work.

How about the effect of dust sublimation? Indeed, dust
grains may sublime in \( \text{H II} \) regions because of the strong
radiation from the central source. However, the radius of
the dust cavity caused by the dust sublimation is about
10^{-4} \text{ pc} (Mookerjea & Ghosh 1999). This is too small to
produce the large cavity expected here. Thus, the dust
sublimation is not dominant mechanism to form the dust
cavity.

In addition, we discuss the effect of the clumpy distribu-
tion of dust. Under the clumpy distribution, which is
more realistic than the smooth one adopted here, we may
produce the ionizing photon fraction determined from
observational data even if the dust clumps exist in the
central area of \( \text{H II} \) regions. However we consider that
there is also the central cavity under the clumpy distri-
bution. This is because the radiation pressure and stellar
wind will blows out the dust clumps from the central area.
We note that the expected radius of the cavity in clumpy
medium may become smaller than the determined one in
the previous section. Such effect of the clumpiness should
be clarified in our future work.

4.2. Detectability of Dust Cavity

As stated by Wright (1973), the best observational test of
the dust cavity model is FIR (or submillimeter) observa-
tions with high angular resolution. Assuming a spherical
and uniform structure, we expect that the dust cavity's
radius is about 0.3 pc for our sample of the Galactic com-
 pact \( \text{H II} \) regions. It corresponds to about 60′′/(D/kpc),
where \( D \) is the distance to the region from us. Here, we
examine the detectability of such dust cavity of 'compact'
or 'ultra-compact' \( \text{H II} \) regions by the present and future
IR facilities.

The future IR observational satellite of Japan, ASTRO-
F (IRIS: Infrared Imaging Surveyor) is planned to launch
in 2004 by the Institute of Space and Astronautical Sci-
e nce of Japan. It will offer modest angular resolutions of
30′′-50′′ at 50–200 \( \mu \text{m} \) (Murakami 1998). We may detect
the dust cavity of \( \text{H II} \) regions located within only about
1 kpc from us. However, ASTRO-F will survey the whole
of the sky, fortunately. Thus, we may detect many such
closest cavities.

SIRTF, which is the major upcoming IR satellite
planned to launch in July 2002 by NASA, offers much
higher angular resolutions of 2.5′′-16′′ at 24–160 \( \mu \text{m} \).\footnote{See http://sirtf.caltech.edu/SSC/}
If we observe the emission from dust being thermally equi-
librium with ambient gas, the super resolution mode at
70 \( \mu \text{m} \), which provides us with 4.9′′ angular resolution, is
the most suitable. By this observing mode, we can detect
the dust cavity of \( \text{H II} \) regions within about 12 kpc from us,
i.e. almost all \( \text{H II} \) regions in our Galaxy. Therefore,
SIRTF will resolve the dust cavity, and clarify the dust
distribution in \( \text{H II} \) regions in detail.

We may also detect the dust cavity at submillimeter. For
example, SCUBA provides us with much higher angu-
lar resolution, 8′′ at 450 μm, or 14.5′′ at 850 μm. Hatchell et al. (2000) observed the Galactic ‘ultra-compact’ H II regions by SCUBA, and present high resolution images of them. Hunter et al. (2000) also present high resolution images of the ‘ultra-compact’ H II regions obtained by Caltech Submillimeter Observatory. However, we cannot find the evidence of the cavity from their images. This may be because the sample regions are ‘ultra-compact’, that is, their densities are very high, so that the radius of the cavity is very small. Indeed, the estimated gas densities of their sample exceed about 10^4 cm^{-3} (Hunter et al. 2000). For such high density region, the Strömgren radius is very small, less than 0.1 pc. It is corresponds to \( \lesssim 5 \)′′ for the typical distance of their sample (about 5 kpc). Since the cavity’s radius is less than the Strömgren radius, the cavity cannot be resolved by their observations. If we select some nearby spherical ‘compact’ H II regions, whose gas densities are about 10^3 cm^{-3}, as the targets, we may detect the dust cavity by SCUBA.

5. CONCLUSIONS

We examine a possible distribution of dust grains in H II regions. Assuming the geometry with the central dust cavity, which is suggested theoretically and observationally in the literature, we can determine the cavity’s radius by using a simple transfer model of Lyman continuum photons in a dusty spherical medium. We adopt the extinction law recently developed by Weingartner & Draine (2001), which is based on two components of grains, carbonaceous and silicate grains, and is a function of the ratio of visual extinction to color excess, \( R_V \). We assume \( R_V = 5.5 \), which is suitable for high density regions. In the transfer model, only one free parameter is included; the radius of the dust cavity.

The fraction of Lyman continuum photons contributing to hydrogen ionization (i.e. ionizing photons) is adopted as a new constraint to determine the cavity’s radius. The ionizing photon fractions of 13 ‘compact’ or ‘ultra-compact’ H II regions in the Galaxy are determined from the ratio of infrared to radio fluxes via the method developed by us recently (Paper I and II). Its mean is 0.55. It is consistent with our previous results; a half of LC photons is absorbed by dust before they ionize the neutral hydrogen.

We examine the effect of various quantities on the relation between the ionizing photon fraction and the dust cavity’s radius. Setting a fixed radius of the cavity, we find that the ionizing photon fraction decreases as the ionization parameter increases. Also we find that the fraction decreases as the value of \( R_V \) decreases or as electron temperature increases.

We determine the dust cavity’s radius of individual sample region so as to reproduce the fraction of ionizing photons estimated from observational data by the transfer model. The mean determined radius of the dust cavity is 0.39 times Strömgren radius for all of the sample. We divide our sample into two subsamples: one is the ‘ultra-compact’ sample, and the other is the ‘compact’ sample. Our classification is based on the Strömgren (or ionized) radius of the sample regions, and is consistent with that of Habing & Israel (1979) based on the gas densities. A typical radius of the dust cavity for the ‘compact’ sample is 0.30 ± 0.12 in units of the Strömgren radius, where the error includes both uncertainties of the individual estimate and the variation among sample regions. This corresponds to about 40% of the ionized radius and about 0.3 pc. Also, a typical cavity’s radius for the ‘ultra-compact’ sample is 0.48 ± 0.26 in units of the the Strömgren radius, which corresponds to about 60% of the ionized radius and about 0.2 pc.

Since the uncertainties of these values are somewhat large and the ‘ultra-compact’ sample consists of only three regions, it is uncertain whether the difference of the cavity’s radius between two subsamples is real and indicates an evolutionary sequence of H II regions. In any case, we can reject the dust distribution without the central cavity with the significance level about 0.001% for both samples. Thus, we conclude that the model nebula filled with dust uniformly is invalid in order to explain the ionizing photon fraction. The dust cavity model is supported independently of the previous works.

We discuss the formation mechanism of the dust cavity. Although the radiation pressure and stellar wind by the central source can produce the central cavity, it is uncertain which is dominant mechanism. On the other hand, the dust sublimation process is not a major mechanism to form the cavity. This is because the expected cavity’s radius by the sublimation process is too small to explain that obtained by us.

We discuss the detectability of the dust cavity by present and future infrared–submillimeter facilities. SIRTF is the most powerful facility to detect the cavity. Indeed, we expect that SIRTF can detect the cavities in almost all H II regions of our Galaxy. SCUBA can also detect the cavities if we select nearby (typically \( \lesssim 5 \) kpc) spherical ‘compact’ H II regions, whose gas densities are about 10^3 cm^{-3}, as the targets. Moreover, Japanese IR satellite, ASTRO-F can detect the cavities in H II regions located within only 1 kpc from us. Since ASTRO-F surveys the whole of the sky, we may detect a lot of closest H II regions with the central cavity.

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Mookerjea, B., & Ghosh, S. K. 1999, BASI, 27, 567
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Yoshida, S., Mizuno, S., Nakano, M., Kogure, T., Sasaki, T., & Wiramihardja, S. D. 1987, in IAU Symp. 115, 189
Table 1
Observational properties of Galactic H ii regions

<table>
<thead>
<tr>
<th>Object</th>
<th>R (kpc)</th>
<th>D (kpc)</th>
<th>S$_{5\text{GHz}}$ (Jy)</th>
<th>F$_{\text{IR}}$ (10$^{-14}$ W cm$^{-2}$)</th>
<th>T$_e$ (K)</th>
<th>n$_e$ (cm$^{-3}$)</th>
<th>Class</th>
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<tr>
<td>G1.13-0.11</td>
<td>0.2</td>
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<td>2.1</td>
<td>5900</td>
<td>1000</td>
<td>C</td>
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<tr>
<td>W31B4</td>
<td>3.2</td>
<td>5.5</td>
<td>2.9</td>
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<td>6800</td>
<td>1000</td>
<td>C</td>
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<td>6000</td>
<td>3500</td>
<td>U</td>
</tr>
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<td>1500</td>
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<td>1600</td>
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<td>1000</td>
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<td>6500</td>
<td>U</td>
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<td>1000</td>
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$^a$Cols.(4), (5), and (7) are averaged by two different observations.

Table 2
Determined properties of Galactic H ii regions

<table>
<thead>
<tr>
<th>Object</th>
<th>$N_{LC}$</th>
<th>$L_{IR}$</th>
<th>$f$</th>
<th>log $U$</th>
<th>$R_S$</th>
<th>$r_i$</th>
<th>$y_d$</th>
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<tbody>
<tr>
<td></td>
<td>(10$^{49}$s$^{-1}$)</td>
<td>(10$^6$L$_\odot$)</td>
<td></td>
<td></td>
<td>(pc)</td>
<td>(pc)</td>
<td></td>
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<td>0.44</td>
<td>-1.94</td>
<td>0.84</td>
<td>0.64</td>
<td>0.18</td>
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<td>0.28</td>
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<td>0.69</td>
<td>0.59</td>
<td>0.38</td>
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<td>G23.95+0.15</td>
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<td>0.24</td>
<td>0.45</td>
<td>-1.89</td>
<td>0.27</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
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<td>2.3</td>
<td>0.28</td>
<td>-1.70</td>
<td>1.00</td>
<td>0.65</td>
<td>0.15</td>
</tr>
<tr>
<td>G25.38-0.18</td>
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<td>2.0</td>
<td>0.38</td>
<td>-1.70</td>
<td>0.92</td>
<td>0.67</td>
<td>0.29</td>
</tr>
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<td>G333.60-0.21</td>
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<td>0.45</td>
<td>-1.58</td>
<td>0.46</td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td>G45.45+0.06</td>
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<td>1.0</td>
<td>0.36</td>
<td>-1.91</td>
<td>1.05</td>
<td>0.75</td>
<td>0.14</td>
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<td>W51e</td>
<td>6.4</td>
<td>2.7</td>
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<td>-1.70</td>
<td>1.07</td>
<td>0.83</td>
<td>0.44</td>
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<td>NGC3576</td>
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<td>0.77</td>
<td>-1.62</td>
<td>0.33</td>
<td>0.30</td>
<td>0.75</td>
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<td>1.2</td>
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<td>1.06</td>
<td>0.89</td>
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<td>0.95</td>
<td>0.75</td>
<td>0.34</td>
</tr>
<tr>
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<td>1.10</td>
<td>1.00</td>
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<td>0.67</td>
<td>-2.31</td>
<td>0.38</td>
<td>0.34</td>
<td>0.22</td>
</tr>
</tbody>
</table>

### Table 3

**Mean properties of ‘compact’ and ‘ultra-compact’ H ii regions**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number</th>
<th>$T_e$ (K)</th>
<th>$n_e$ (cm$^{-3}$)</th>
<th>$N_{LC}$ ($10^{49}$ cm$^{-1}$)</th>
<th>$R_S$ (pc)</th>
<th>$r_i$ (pc)</th>
<th>$f$</th>
<th>$y_d$</th>
<th>$r_d/r_i$</th>
<th>$r_d$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>compact</td>
<td>8</td>
<td>6600</td>
<td>1200</td>
<td>6.8</td>
<td>0.95</td>
<td>0.72</td>
<td>0.45</td>
<td>0.30</td>
<td>0.38</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>±630</td>
<td>±400</td>
<td>±3.9</td>
<td>±0.13</td>
<td>±0.098</td>
<td>±0.10</td>
<td>±0.12</td>
<td>±0.14</td>
<td>±0.13</td>
<td>±0.13</td>
</tr>
<tr>
<td>ultra-compact</td>
<td>3</td>
<td>6600</td>
<td>4800</td>
<td>5.4</td>
<td>0.35</td>
<td>0.29</td>
<td>0.56</td>
<td>0.48</td>
<td>0.57</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>±1100</td>
<td>±1200</td>
<td>±3.2</td>
<td>±0.073</td>
<td>±0.062</td>
<td>±0.15</td>
<td>±0.21</td>
<td>±0.20</td>
<td>±0.080</td>
<td>±0.080</td>
</tr>
</tbody>
</table>

**Note.** — Col.(2): Number of sample regions. Col.(5): Intrinsic production rate of Lyman continuum photons Col.(7): Ionized radius in parsec unit. Col.(10): Ratio of the cavity’s radius to ionized radius. Col.(11): Cavity’s radius in parsec unit. We also show the standard deviations of all quantities.
Dust in H II Regions

Table 4
Mean dust cavity’s radius for various $R_V$

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R_V$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.5</td>
<td>4.0</td>
<td>3.1</td>
</tr>
<tr>
<td>all</td>
<td>0.39</td>
<td>0.50</td>
<td>0.58</td>
</tr>
<tr>
<td>compact</td>
<td>0.30</td>
<td>0.43</td>
<td>0.52</td>
</tr>
<tr>
<td>ultra-compact</td>
<td>0.48</td>
<td>0.57</td>
<td>0.63</td>
</tr>
</tbody>
</table>
Fig. 1.— Model calculation of ionizing photon fraction, $f$, as a function of the dust cavity’s radius in unit of the Strömgren radius, $y_d$. For all panels, the dotted, solid, and dashed lines represent the cases of the logarithmic ionization parameter, $U$, of -2.5, -2.0, and -1.5, respectively. The electron temperature, $T_e$, is set to be 6600 K. In panels (a), (b), and (c), we show the cases of the ratio of visual extinction to color excess, $R_V = 3.1$, 4.0, and 5.5, respectively.
Fig. 2.— Same as Figure 1. In panel (a), we show the variation of the $f$-$y_d$ relation of the case of $\log U = -2.0$ and $T_e = 6600$ K for various $R_V$ values. In panel (b), we show the variation of the case of $\log U = -2.0$ and $R_V = 5.5$ for various $T_e$. 

Dust in H II Regions
Fig. 3.— Histograms of the determined quantities. (a) Ionizing photon fraction. (b) logarithmic ionization parameter. (c) Strömgren radius in parsec unit. (d) Ionized radius in parsec unit. (e) Dust cavity’s radius in unit of the Strömgren radius. The white histograms represents the ‘compact’ H ii regions sample, and the shaded histograms represents the ‘ultra-compact’ sample. The dotted histograms are two objects removed from further discussions.