Conversion Law of Infrared Luminosity to Star Formation Rate for Galaxies

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Abstract

We construct a new algorithm for estimating the star formation rate (SFR) of galaxies from their infrared (IR) luminosity by developing the theory of the IR emission from a dusty H II region. The derived formula is \[ \text{SFR}/(M_\odot \text{yr}^{-1}) = \left\{ 3.3 \times 10^{-10}(1 - \eta)/(0.4 - 0.2f + 0.6\epsilon) \right\} (L_{\text{IR}}/L_\odot), \] where \( f \) is the fraction of ionizing photons absorbed by hydrogen, \( \epsilon \) is the efficiency of dust absorption for nonionizing photons from OB stars, and \( \eta \) is the cirrus fraction of observed IR luminosity. The previous conversion formulae of SFR from the IR luminosity is applicable to only the case where the observed IR luminosity is nearly equal to the bolometric luminosity (starburst galaxies etc.), except for some empirical formulae. On the other hand, our theoretical SFR is applicable to galaxies even with a moderate star formation activity. That is, our simple and convenient formula is significantly useful for estimating the SFR of various morphologies and types of galaxies — from early elliptical to late spiral and irregular galaxies, or from active starburst to quiescent galaxies — as far as they have neither an abnormal dust-to-gas ratio nor an evident active galactic nucleus.

Key words: galaxies: fundamental parameters — infrared: galaxies — ISM: dust — stars: formation — methods: analytical

1. Introduction

There are a number of studies estimating the star formation rate (SFR) of galaxies by using various observational quantities. Indeed, we can estimate the SFR from colors of galaxies, hydrogen recombination lines, ultraviolet (UV) continuum and so on (Kennicutt 1998a). Of course, infrared (IR) radiation is also a very important tracer of the SFR. This is because some fraction of ionizing and nonionizing photons from star forming regions are absorbed by dust grains which exist in or nearby these regions, and their energy is reradiated in IR spectral range (Soifer et al. 1987).

In fact, most active star forming galaxies emit almost all of their radiative energy in IR (Soifer et al. 1987). For such galaxies, we can assume that their observed IR luminosity is nearly equal to their bolometric luminosity. By adopting this assumption and a proper population synthesis model, Kennicutt (1998b) and Thronson & Telesco (1986) have estimated SFRs from the IR luminosity for starburst galaxies and for active dwarf galaxies, respectively. Likewise, taking into account the energy balance of such active star forming galaxies, we can also calculate their SFR from the IR luminosity (Devereux & Young 1991).

For normal galaxies with a moderate star formation activity, however, the situation is more complex, because we can no longer assume their IR luminosity to be their bolometric one. In such cases, only empirical methods have been made to date. For example, Buat & Xu (1996) determined the SFR in terms of the far-IR luminosity, calculating the ratio of it to the UV luminosity. However, their SFR is valid for late (Sb–) spiral galaxies only, since the ratio of far-IR to UV luminosity for early spiral (Sa–Sab) galaxies systematically differs from that for late spiral galaxies. Thus, we will establish more general method for the estimation of the SFR from the IR luminosity in this Letter.

In general, we consider that massive young stars are formed in H II regions. In many H II regions, IR radiation is detected and it has a good correlation with thermal free-free radio emission, which comes directly from the ionized regions and is directly related to massive star formation (e.g., Spitzer 1978). Therefore, dust grains exist in or nearby H II regions, and they absorb a part of radiation from young massive stars and reradiate this absorbed energy in IR wavelengths. Petrosian et al. (1972) estimated the IR luminosity radiated from dusty H II regions with a simple analytic approximation. Our analysis

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is based on their result.

Unfortunately, not all the IR radiation originates from star forming regions in galaxies. The observed IR radiation from dust is the sum of the “warm” component distributed in or nearby star forming regions and the “cool” component (called cirrus component) distributed diffusely in the interstellar medium far from such regions (e.g., Helou 1986). Thus, the SFR calculated from the observed total IR luminosity is clearly overestimated. When we estimate the SFR from IR luminosity, in this case, the cirrus component must be subtracted. In this Letter, we will subtract the cirrus component according to Lonsdale-Persson & Helou (1987), which presented a model of the cirrus fraction by using the ratio of IRAS 60µm and 100µm fluxes. Also, we can estimate this fraction by applying a proper radiative transfer model for reproducing multi-wavelength data of galaxies (e.g., Silva et al. 1998, Efstathiou et al. 2000). However, the fraction of the cirrus component remains still uncertain.

We stress again that only empirical studies on SFR from the IR luminosity of galaxies with a moderate star formation activity have been made to date. Thus, we develop the result of Petrosian et al. (1972) and construct a new algorithm to derive the SFR from the IR luminosity in this Letter. Thereby, we obtain a convenient formula, and calculate the SFR of galaxies from their IR luminosity. This Letter contains the following sections: we review the IR luminosity of a dusty H II region in §2, our formula of SFR is constructed in §3, we discuss some results derived from our formula in §4, and the conclusions of this Letter are summarized in the last section.

2. Infrared Luminosity of H II regions

First of all, let us look closely at the wavelength range of IR radiation from H II regions. We consider IR radiation to be mainly thermal black body radiation of dust heated by young massive stars in such regions. In fact, IR spectral energy distribution (SED) observed in H II regions can be fitted by the black body radiation of about 30–50 K (Soifer et al. 1987). By the way, the temperature of dust within ionized regions is higher than that of dust out of there. That is, the peak wavelength of dust-IR radiation depends on the distance of dust grains from ionizing stars. It is, however, complex to take account of more than two temperatures of dust and this is beyond the scope of this Letter. Instead of determining exact SED, we consider the dust luminosity in the whole range of 8–1000 µm, which covers almost all the emission from dust. The increment owing to stars at the shorter wavelength in this range is assumed to be subtracted.

Next, we see the result of Petrosian et al. (1972). When the Case B approximation, which is an assumption of the large optical depth for every Lyman-emission-line photon (e.g., Osterbrock 1989), can be applied to a dusty H II region, Petrosian et al. (1972) derived the following equation for the dust-IR luminosity, $L_{\text{IR}}^{\text{dust}}(8–1000\mu m)$,

$$L_{\text{IR}}^{\text{dust}}(8–1000\mu m) = L(\text{Ly}\alpha) + (1 - f)\langle h\nu \rangle_{\text{ion}} S + L_{\text{nonion}}(1 - e^{-\tau}). \tag{1}$$

Here, $L(\text{Ly}\alpha)$ is the luminosity of Lyman-α emission line, $f$ is the fraction of ionizing photons absorbed by hydrogen, $\langle h\nu \rangle_{\text{ion}}$ is the averaged energy of ionizing photons, $S$ is the number of ionizing photons from central sources per unit time, $L_{\text{nonion}}$ is the luminosity of nonionizing photons, and $\tau$ is the optical depth of dust for nonionizing photons.

They assumed that all Lyman-α photons produced by hydrogen recombination processes in a H II region are absorbed by dust within this region and reemitted as IR radiation because of their large optical depth (i.e. Case B). This is reflected in the first term of the right hand side of equation (1). The second term represents the energy of ionizing photons absorbed directly by dust within the ionized region. Then, the last term denotes the energy of nonionizing radiation absorbed by dust in or nearby ionized region, especially, in molecular clouds surrounding this region.

We now consider the luminosity of the Lyman-α emission line within H II regions. Under Case B approximation, every ionizing photon will eventually form one hydrogen atom with the $n = 2$ level. In this process, about two-thirds of recombining electrons will reach the 2p state and go down to 1s, emitting a Lyman-α photon. The remaining one-third of recombining electrons will reach the 2s state, and two continuum photons will be emitted simultaneously within 1 second because the transition from the 2s to the 1s is forbidden for any one photon process (e.g., Spitzer 1978). Thus, $L(\text{Ly}\alpha)$ in terms of $S$ is $0.67h\nu_{\text{Ly}\alpha}/S$, where $\nu_{\text{Ly}\alpha}$ is the frequency at the Lyman-α emission.

The luminosity of ionizing photons from central sources, $L_{\text{ion}}$, is written as $\langle h\nu \rangle_{\text{ion}} S$. When we set $h\nu_{\text{Ly}\alpha}=10.2$ eV and $\langle h\nu \rangle_{\text{ion}} \sim 15$ eV, the luminosity of Lyman-α is given by

$$L(\text{Ly}\alpha) = 0.67 \frac{h\nu_{\text{Ly}\alpha}}{\langle h\nu \rangle_{\text{ion}}} fL_{\text{ion}} \simeq 0.45fL_{\text{ion}}. \tag{2}$$

Therefore, equation (1) is reduced to

$$L_{\text{IR}}^{\text{dust}}(8–1000\mu m) = (1 - 0.55f)L_{\text{ion}} + \epsilon L_{\text{nonion}}, \tag{3}$$

where $\epsilon \equiv 1 - e^{-\tau}$ is an averaged dust-absorption-efficiency of nonionizing photons from central sources in H II regions.

3. Derivation of Star Formation Rate

We will derive a new convenient formula to determine the SFR from the observed IR luminosity. Our result
is presented in equation (13) in this section. First, in
order to estimate the recent SFR, we assume that all
of the total energy radiated from star forming regions
is emitted by only young massive stars with the spectral
types of O and B on the main-sequence. We fit the mass-
luminosity relation of main-sequence stars from the table
3.13 in Binney & Merrifield (1998) as

$$\log l(m) = \begin{cases} \log m + 4 & \text{for } m \geq 20M_\odot, \\ 4 \log m & \text{for } m < 20M_\odot, \end{cases}$$

(4)

where $m$ is the stellar mass in solar unit and $l(m)$ is the
stellar luminosity in solar unit as a function of $m$.

We now must choose a initial mass function (IMF),
$\psi(m)$, but the choice of it may affect our calculation of
the SFR. There are two uncertainties in adopting a spe-
cific IMF: the slope of $\psi(m)$, and the upper and lower
cut-off of $m$. In this Letter, we adopt the Salpeter’s
IMF, $\psi(m) \propto (m/M_\odot)^{-2.35}$ (Salpeter 1955) and the mass
range of 0.1 – 100 $M_\odot$, since they seem to be widely ap-
licable. We normalize the IMF by $\int \psi(m) dm = 1$. We
will discuss the uncertainty about the choice of an IMF
more closely in §4.

Next, we consider the mass range of O stars is 20 – 100
$M_\odot$ and that of B stars is 3 – 20 $M_\odot$. Assuming that the
total luminosity from star forming regions, $L_{total}^{bol}$, is the
bolometric luminosity of O and B stars, $L_{OB}^{bol}$, we obtain

$$L_{total}^{bol} = L_{OB}^{bol} = a \int_{3M_*}^{100M_*} l(m)\psi(m) dm,$$

(5)

where $a$ is a normalization so that $M_* = a \int m \psi(m) dm$,
when we represent $M_*$ as the stellar mass formed newly
in star forming regions. Since we adopt the Salpeter’s
IMF, the bolometric luminosity of O stars and that of B
stars are determined as $L_{Otype}^{bol} = 0.8L_{OB}^{bol}$ and $L_{Btype}^{bol} =
0.2L_{OB}^{bol}$, respectively.

Let us discuss what type of stars emits ionizing pho-
tons dominantly. According to a model calculation by
Panagia (1973), main-sequence stars of B type hardly
emit these photons whereas those of O type radiate them.
However, not all photons from O type stars have shorter
wavelength than Lyman limit (912Å). The energy frac-
tion of ionizing photons from O5 stars is 0.6 and that of
O9 stars is 0.2 (Panagia 1973). Then, if we adopt 60 $M_\odot$
and 20 $M_\odot$ as the mass of O5 and O9 stars, respectively,
and when the energy fraction of ionizing photons from stars
of mass $m$ is denoted by $\alpha(m)$, we get the following
relation approximately,

$$\alpha(m/M_\odot) = 0.01(m/M_\odot).$$

(6)

Using equation (6), we can calculate the ionizing lumi-
nosity of main-sequence O type stars. Then, we get
$L_{ion}^{Otype} = 0.5L_{Otype}^{bol}$ and $L_{ion}^{OB} = 0.4L_{OB}^{bol}$. Now we assume that
B type stars radiate nonionizing photons only. That is,

$$L_{ion} = L_{Otype}^{ion}.$$
Finally, from equations (3) and (4), we derive the following formula for the SFR of a galaxy in terms of its dust-IR luminosity by adopting $3.3 \times 10^6$yr of the star formation time-scale,

$$\frac{\text{SFR}}{M_\odot \text{yr}^{-1}} = \frac{3.3 \times 10^{-10}(1 - \eta) L_{\text{IR}}^{\text{obs}}(8 - 1000 \mu \text{m})}{0.4 - 0.2 f + 0.6 \epsilon} \times L_\odot.$$  (13)

This is the main result of this Letter.

4. Discussions

As stated in §1, the previous works on the SFR in IR luminosity is not applicable to galaxies with a moderate star formation activity, because we can no longer assume their IR luminosity to be their bolometric one for such galaxies. On the contrary, our equation (13) is also reasonable for them. As a demonstration of our equation (13), hence, we apply it to galaxies with a moderate star formation activity. We can adopt the suitable sample with the data set of the IRAS luminosity, $L_{\text{IR}}^{\text{obs}}(40 - 120 \mu \text{m})$, in Usui et al. (1998), for example. Their sample contains 15 early (Sa–Sab) spiral galaxies showing rather high star forming activity in far-IR, and their averaged IRAS luminosity is about $5.8 \times 10^9 L_\odot$.

For absorbing fraction by neutral hydrogen, $f$, we adopt 0.26 derived by Petrosian et al. (1972) for Orion nebula. The efficiency of dust absorption for nonionizing photons, $\epsilon$, is estimated to be 0.6 from the averaged 1000–4000 Å extinction curve of the Galaxy (Savage & Mathis 1979) and the average visual extinction of Usui’s sample ($A_V = 1$ mag from private communication with Usui). Here, we should note that when our formula is applied to the individual molecular clouds, these parameters may depend on the geometry of clouds. Moreover, we choose 0.5 for the cirrus fraction, $\eta$, of Usui’s sample, according to a model of Lonsdale-Persson & Helou (1987). In addition, we have converted $L_{\text{IR}}^{\text{obs}}(8 - 1000 \mu \text{m})$ to $L_{\text{IR}}^{\text{obs}}(40 - 120 \mu \text{m})$ calculated easily from IRAS 60 and 100 $\mu$ m fluxes by the factor of 1.4, assuming the modified black body radiation ($I_\nu \propto \nu^{2}$, where $I_\nu$, $\nu$, and $B_\nu$ are intensity, frequency, and the Plank function, respectively) of 30 K from an optically thin dust medium. Of course, this factor depends on the dust temperature. For example, if we assume 50 K and 15 K, the factors are changed to 1.1 and 5.6, respectively. Thus, we must note this point when our formula is applied to galaxies whose IR emission is dominated by almost only cold dust (e.g., 15 K) owing to their quiescent star forming activity.

Accordingly we obtain $2 M_\odot \text{yr}^{-1}$ as the average value for the sample galaxies in Usui et al. (1998). This SFR is very similar to the value, $1.4 M_\odot \text{yr}^{-1}$, for the same sample via the equation for starburst galaxies in Kennicutt (1998b). Thus, we find coincidence between the two estimated SFRs. This coincidence originates from the following two reasons. [1] The coefficient of conversion from IR luminosity to SFR tends to decrease due to the cirrus fraction of IR. [2] It also tends to increase due to the lower optical depth of dust. Thus, we suggest that since the effect of the cirrus fraction is very effective, that of the lower optical depth of dust is offset for adopted early spiral galaxies.

Now we will discuss what type of galaxies our result can be applied to. Our algorithm starts from the expected dust-IR luminosity of an H II region. There, we assume that the dust content is enough to absorb Lyman-α photons before they run away from this region. For most observed H II region, the Case B approximation is applicable, thus, all Lyman-α photons will be absorbed by dust within this region, even with a relatively low amount of dust (Spitzer 1978). Hence, equation (13) can be applied to galaxies with star formation in H II regions if they have neither an extremely small dust-to-gas ratio nor an active galactic nucleus (AGN). However, we can adapt equation (13) to the AGN plus star forming galaxies, subtracting the AGN component of dust-IR luminosity from the observed IR luminosity. On the other hand, the limit of dust-to-gas ratio for the application of equation (13) will be examined in our future work.

Finally, we discuss the choice of an IMF, and an upper and lower cut-offs of mass. We examine the effect of variance of the IMF, the upper limit mass or the lower limit mass. When we change only the IMF for the Scalo’s IMF obtained from Binney & Merrifield (1998), the coefficient of the equation (13) is smaller than that of the Salpeter’s IMF by the factor of 0.8. If we substitute $60 M_\odot$ into the upper limit mass, the recent SFR for the sample of Usui et al. (1998) becomes 1.4 times larger than that of 100 $M_\odot$. If the lower cut off mass is set 1 $M_\odot$, the coefficient of the equation (13) decrease by the factor of 0.4. In summary, the choices of an IMF, an upper limit mass and a lower limit mass cause uncertainties of the factor of about 2 to our result.

5. Conclusions

We summarize the conclusions reached in this Letter:

1. Starting from the dust-IR luminosity expected theoretically from a dusty H II region with the Case B approximation, we formulate equation (13) to estimate the SFR of galaxies from their observed IR luminosity.

2. This new simple formula for SFR contains three parameters explicitly: [1] the fraction of ionizing photons from young massive stars absorbed by neutral hydrogen in star forming regions, $f$, [2] the averaged efficiency of dust absorption for nonionizing photons from young massive stars, $\epsilon$, and [3] the cirrus fraction of observed IR luminosity, $\eta$.

3. Using equation (13) and adopting a proper set of three parameters, the recent SFR averaged for the sam-
ple in Usui et al. (1998), which consists of 15 early (Sa–Sab) spiral galaxies with moderate IR luminosity ($\sim 10^{9-10} L_\odot$), is calculated to be about $2 M_\odot \text{yr}^{-1}$.

4. The derived convenient equation (13) is applied to any galaxies forming young massive stars in H II regions as far as they have neither an extremely small dust-to-gas ratio nor an AGN, if we choose a set of parameters reasonable for applied galaxies.

5. The coefficient of equation (13) has uncertainty of the factor of about 2 by the choices of a specific IMF, and its upper and lower limits of stellar mass.

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