Low-Metallicity Star Formation: From the First Stars to Dwarf Galaxies
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The size-density relation of H II regions in blue compact dwarf galaxies

Hiroyuki Hirashita[1] **and Leslie K. Hunt**[2]

[1]Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan, R.O.C.
email: hirashita@asiaa.sinica.edu.tw

[2]INAF - Istituto di Radioastronomia/Sezione Firenze, Largo E. Fermi, 5, 50125 Firenze, Italy
email: hunt@arcetri.astro.it

Abstract. We investigate the size-density relation of H II regions in blue compact dwarf galaxies (BCDs) by compiling observational data of their size ($D_{\rm i}$) and electron density ($n_{\rm e}$). We find that the size-density relation follows a relation with constant column density ($n_{\rm e} \propto D_{\rm i}^{-1}$) rather than with constant luminosity ($n_{\rm e} \propto D_{\rm i}^{-1.5}$). Such behavior resembles that of Galactic H II regions, and may imply an underlying "scale-free" connection. Because this size-density relation cannot be explained by static models, we model and examine the evolution of the size-density relation of H II regions by considering the star formation history and pressure-driven expansion of H II regions. We find that the size-density relation of the entire BCD sample does not result from an evolutionary sequence of H II regions but rather reflects a sequence with different initial gas densities (or "hierarchy" of density). We also find that the dust extinction of ionizing photons is significant for the BCD sample, despite their blue optical colors. This means that as long as the emission from H II regions is used to trace massive star formation, we would miss the star formation activity in dense environments even in low-metallicity galaxies such as BCDs.

Keywords. dust, extinction, galaxies: dwarf, galaxies: evolution, galaxies: ISM, galaxies: star clusters, HII regions

1. Introduction

H II regions are a class of objects important in studying star formation activity; they are ionized by young massive stars, which trace recent star formation. However, our knowledge of extragalactic H II regions is still lacking compared with that of Galactic H II regions because of relative observational difficulties. Moreover, physical properties of extragalactic H II regions have a wider spread than those of Galactic H II regions.

The total mass of massive stars (sources of ionizing photons) can be observationally quantified by estimating the number of ionizing photons. A simple argument of a Strömgren sphere indicates that $\dot{N}_{\rm ion} \propto D_{\rm i}^3 n_{\rm e}^2$, where $\dot{N}_{\rm ion}$ is the number of ionizing photons emitted per unit time, $D_{\rm i}$ is the diameter of the H II region, and $n_{\rm e}$ is the electron number density in the H II region. Thus, in principle, by examining $n_{\rm e}$ and $D_{\rm i}$ of an H II region, we can estimate the ionizing photon luminosity. Observationally, the diameter ($D_{\rm i}$) and the electron density ($n_{\rm e}$) of Galactic H II regions are known to have a relation roughly fitted by $n_{\rm e} \propto D_{\rm i}^{-1}$ (e.g., Garay & Lizano 1999), while the above argument of the Strömgren sphere indicates that $n_{\rm e} \propto D_{\rm i}^{-1.5}$ if $\dot{N}_{\rm ion}$ is constant.

It is surprising that the size-density relation of extragalactic H II regions also follows $n_{\rm e} \propto D^{-1}$ as shown by Hunt *et al.* (2003) for blue compact dwarf galaxies (BCDs), although the relation is *scaled-up* compared with the Galactic H II regions. The relation $n_{\rm e} \propto D^{-1}$ is interpreted as a *constant ionized-gas column density*. However, the physical mechanism that reproduces a constant column density has never been clarified. Since some BCDs have intense star formation activity represented by super star clusters (e.g., Thuan *et al.* 1997), which are never seen in the Galactic disk, extragalactic H II regions, especially those in BCDs, enable us to examine the properties of H II regions over a wide range of the ionizing photon luminosity, spatial extent, etc. Since BCDs have generally low metallicity, giant H II regions in BCDs may be used as a "test bench" of high-redshift intense star formation at the early stage of chemical evolution.

2. Data

We adopt the sample in Hunt *et al.* (2003), who measure the sizes ($D_{\rm i}$) of BCDs by using the archival data of the *Hubble Space Telescope* (*HST*). The electron number density $n_{\rm e}$ is measured optically, and taken from the literature. This sample is called *HST* sample. In order to examine the compact extremes of our models, we also incorporate some high-resolution radio data of BCDs from the literature, with sizes and densities inferred from the high-frequency thermal radio continuum (see Hirashita & Hunt 2008, hereafter HH08). Finally, in addition to BCDs, we include H II region data of other types of galaxies from the literature.

Fig. 1 (HH08 for more details) shows the trends of the data. The Galactic sample of Kim & Koo (2001), as noted by them, can be fitted by $n_{\rm e} \propto D_{\rm i}^{-1}$. The H II regions in BCDs follow a similar size-density relation with the same slope (power-law index), but scaled-up relative to the Galactic one.

The power-law size-density relation of H II regions indicates that the star formation is self-similar, that is, there is no characteristic scale of star formation. This scale-free

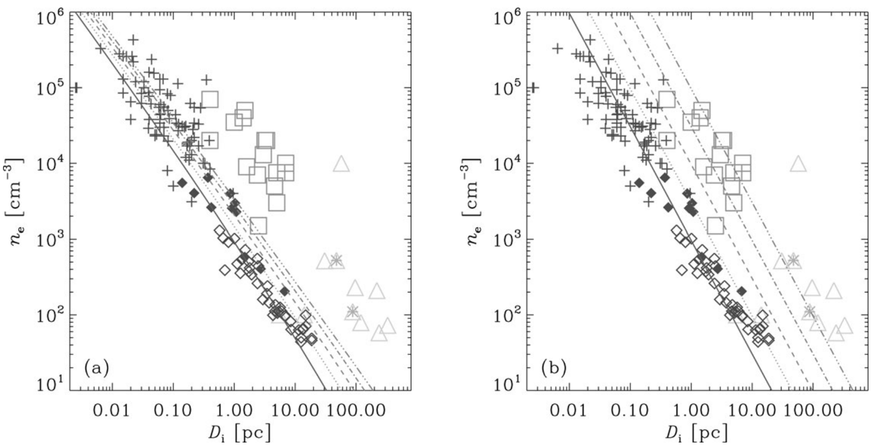

Figure 1. Relation between the electron number density $n_{\rm e}$ and the ionization diameter $D_{\rm i}$ for various samples. The open triangles and open squares show the data of the *HST* sample and the radio sample of blue compact dwarf galaxies, respectively. The two data points with asterisk correspond to SBS 0335−052 (the upper) and I Zw 18 (the lower). The Galactic H II regions are shown by the crosses (Garay & Lizano 1999) and the open diamonds (Kim & Koo 2001). The filled diamonds correspond to the sample of the Small Magellanic Cloud. In addition to the observational data, some theoretical predictions in the static models are shown in each panel: (a) The solid, dotted, dashed, dot-dashed, and dot-dot-dot-dashed lines present the results with $\dot{N}_{\rm ion} = 3 \times 10^{49}$, 3×10^{50}, 3×10^{51}, 3×10^{52}, and 3×10^{53} s^{-1}, respectively. The Galactic dust-to-gas ratio ($\kappa = 1$) is assumed. (b) Same as Panel (a) but with a lower dust-to-gas ratio ($\kappa = 0.1$).

nature of H II regions is supported by the data for He 2−10 and SBS 0335−052, two of the HST sample; they both host compact dense H II regions when probed by radio high-resolution observations, but appear larger and more tenuous with HST. This means that the same regions when traced with higher spatial resolution turn out to be denser and smaller, but as shown above they follow the same size-density relation as that of larger complexes.

3. Static models

We interpret the size-density relation of the H II regions compiled in the previous section. Here, we basically relate the size and density of H II regions by using the Strömgren sphere, where an ionizing source in a uniform and static medium is assumed (Spitzer 1978). We also include the effect of dust extinction, which is suggested to be important in determining the size of H II regions (e.g., Inoue *et al.* 2001). Since we treat static H II regions in this section, the models described here are called static models. The detailed formulation can be found in HH08 and here we only review some important features.

The most important parameter for the model is the extinction over the Strömgren radius, $\tau_{\rm Sd}$, estimated as (Hirashita *et al.* 2001)

$$\tau_{\rm Sd} = 0.87 \left(\frac{\mathcal{D}}{6\times 10^{-3}}\right)\left(\frac{n_{\rm H}}{10^{2}~{\rm cm^{-3}}}\right)^{1/3}\left(\frac{\dot{N}_{\rm ion}}{10^{48}~{\rm s^{-1}}}\right)^{1/3}, \tag{3.1}$$

where $\mathcal{D}$ is the dust-to-gas mass ratio, $n_{\rm H}$ is the number density of hydrogen nuclei, and $\dot{N}_{\rm ion}$ is the number of ionizing photons emitted per unit time. We assume the dust-to-gas ratio of the solar neighborhood to be $\mathcal{D}_\odot = 6\times 10^{-3}$ (Spitzer 1978). We adopt various constant values for $\mathcal{D}$ and do not follow the time evolution of $\mathcal{D}$ in order to avoid uncertainty concerning the chemical evolution models. For convenience, we define the dust-to-gas ratio normalized to the solar neighborhood value, κ, as

$$\kappa \equiv \mathcal{D}/\mathcal{D}_\odot\,. \tag{3.2}$$

In Fig. 1, the results of the static models are plotted over the observational samples for various $\dot{N}_{\rm ion}$ ($D_{\rm i}$ is the diameter of the ionized region, and $n_{\rm e}$ is the electron number density). In Fig. 1a, the dust-to-gas ratio is assumed to be Galactic ($\kappa = 1$), while in Fig. 1b, $\kappa = 0.1$ is adopted to take into account the low metal content of the BCD sample. As shown in Fig. 1a, the size-density relation is relatively insensitive to the change of $\dot{N}_{\rm ion}$, since most of the ionizing photons are absorbed by dust grains. Because of this weak dependence of $D_{\rm i}$ on $\dot{N}_{\rm ion}$, it is extremely difficult to explain the data of the extragalactic sample, unless we assume an extremely large $\dot{N}_{\rm ion}$. However, the size-density relation of the BCDs, is explained quite easily if we assume a lower dust-to-gas ratio typical of the BCD sample ($\kappa = 0.1$). For this value of dust-to-gas ratio, $D_{\rm i}$ increases almost in proportion to $\dot{N}_{\rm ion}^{1/3}$.

If dust extinction were absent, the size-density relation under a constant $\dot{N}_{\rm ion}$ would follow $n_{\rm e} \propto D_{\rm i}^{-3/2}$. However, both Galactic and extragalactic H II regions have a shallower slope than $n_{\rm e} \propto D_{\rm i}^{-3/2}$ in the size-density relation. Both samples show $n_{\rm e} \propto D_{\rm i}^{-1}$ rather than $n_{\rm e} \propto D_{\rm i}^{-3/2}$, and cannot be explained by a constant $\dot{N}_{\rm ion}$. This implies that the size-density relation is almost certainly not a sequence with a constant $\dot{N}_{\rm ion}$. Rather it is probable that the relation should be considered with varying $\dot{N}_{\rm ion}$, and we examine this in the following.

4. Evolution

The evolution of $\dot{N}_{\rm ion}$ is calculated based on Hirashita & Hunt (2006) under a given star formation history (SFH). We extend our models to include the effect of dust extinction according to Arthur *et al.* (2004). Indeed, dust extinction significantly reduces the size of H II regions especially for compact ones. The details of the formulation are found in HH08.

We choose the initial hydrogen number density, $n_{\rm H0}$, and the gas mass, $M_{\rm gas}$, so that the results are consistent with the sizes, densities, and star formation rates of SBS 0335−052 and I Zw 18. The models calculated with these initial conditions are called the SBS 0335−052 model and the I Zw 18 model, and the selected values are $n_{\rm H0} = 7 \times 10^3$ cm^{-3} and $M_{\rm gas} = 8.1 \times 10^6\ M_\odot$ for the former and $n_{\rm H0} = 100$ cm^{-3} and $M_{\rm gas} = 1.4 \times 10^7\ M_\odot$ for the latter. We also examine a case with $n_{\rm H0} = 10^5$ cm^{-3} and $M_{\rm gas} = 10^7\ M_\odot$ to investigate the dense gas of the radio sample.

In Figs. 2a and b, we show the time evolution of the ionized region on the size-density diagram for the constant SFH and the exponentially decaying SFH, respectively. The evolutionary track in the size-density diagram explains the upper locus of *HST* data including SBS 0335−052 with an age of ∼ 3–10 Myr. Such dense and compact BCDs are classified as "active" in Hunt *et al.* (2003). The I Zw 18 model reproduces the lower part of the BCD sample, and such relatively low-density and diffuse BCDs are called "passive". Therefore, those two classes should have different initial conditions. This picture is consistent with Hirashita & Hunt (2006).

We also observe that the results from the highest initial density reproduce the data points of the radio sample. This means that the radio sample can be understood as an extension of the "active" BCDs toward higher density. Since we assume a similar gas mass among compact sources, SBS 0335−052, and I Zw 18, the observational data

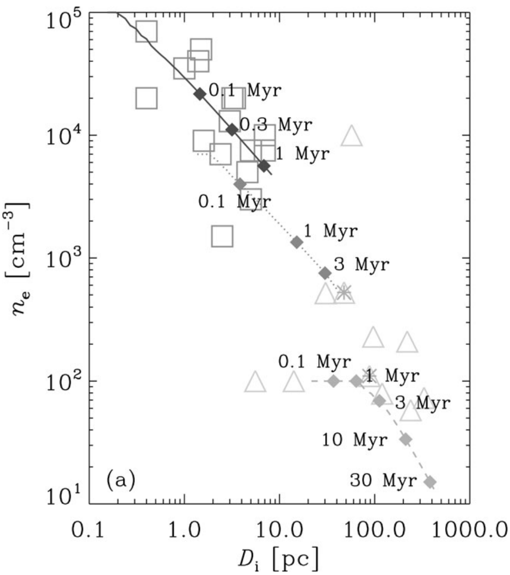

Figure 2. Relation between the electron number density $n_{\rm e}$ and the ionization diameter $D_{\rm i}$ for (a) the constant SFH and (b) the exponentially decaying SFH. The models for compact sources, SBS 0335−052, and I Zw 18 are shown by the solid, dotted, and dashed lines, respectively. The ages are indicated on the corresponding points. The open triangles and open squares are the observational data of the *HST* sample and the radio sample, respectively. The two data points with asterisk correspond to SBS 0335−052 (the upper) and I Zw 18 (the lower).

implies that all the sample is converting $10^7\ M_\odot$ of gas to stars. This may indicate that the final stellar mass formed as a result of the current star formation in the radio sample is comparable to the star formation activity traced in the optical. Thus, we should recognize the importance of embedded compact H II regions such as the radio sample.

5. Summary and discussion

We have investigated the size-density relation of H II regions in BCDs. Motivated by the observed size-density relation, $n_{\rm e} \propto D_{\rm i}^{-1}$, we have modeled and examined the size-density relation of ionized regions by considering the star formation history and pressure-driven expansion of H II regions. By comparing the results with the observed size-density relation of BCDs, we have shown that the entire sample cannot be understood as an evolutionary sequence with a single initial condition. But rather, the size-density relation reflects a sequence with different initial gas densities.

We have also found that the extinction of extragalactic H II regions is also significant. Thus, the H II regions can be regarded as "dust-extinction limited", in the sense that the dust optical depth of the ionizing photons is roughly of order unity. This is consistent with the observed size-density relation of H II regions which follows a constant column density of ionized gas. The dust extinction of ionizing photons is particularly severe over the entire lifetime of the compact radio sample with typical densities of $\gtrsim 10^4\ {\rm cm}^{-3}$. This means that the compact radio sample constitutes a different population from the *HST* one and that we would tend to miss the star formation activity in such dense regions if we use the emission from H II regions (hydrogen recombination lines, free-free continuum) as indicators of star formation rate.

Our results may have a great impact in the cosmological context. Our sample has a similar mass to the building blocks in the Universe. The escape of ionizing photons from them is considered to have contributed to reionize the Universe at high redshift. We have shown that even in low-metallicity galaxies, the dust extinction of ionizing photons is significant. If the same situation holds for high-redshift building blocks, dust may significantly affect the escape fraction of ionizing photons. This highlights the importance of studying dust enrichment in the early Universe. ALMA will be a useful tool to detect the light reprocessed by dust grains. Hirashita *et al.* (2008) have already analyzed data of far-infrared dust emission for a sample of BCDs. Such far-infrared data of nearby metal-poor objects are useful to construct strategies for ALMA observations of high-redshift galaxies.

References

Arthur, S. J., Kurtz, S. E., Franco, J., & Albarrán, M. Y. 2004, *ApJ*, 608, 282

Garay, G., & Lizano, S. 1999, *PASP*, 111, 1049

Hirashita, H., & Hunt, L. K. 2006, *A&A*, 460, 67

Hirashita, H., & Hunt, L. K. 2008, *A&A*, to be submitted (HH08)

Hirashita, H., Inoue, A. K., Kamaya, H., & Shibai, H. 2001, *A&A*, 366, 83

Hirashita, H., Kaneda, H., Onaka, T., & Suzuki, T. 2008, *PASJ*, accepted

Hunt, L. K., Hirashita, H., Thuan, T. X., Izotov, Y. I., & Vanzi, L. 2003, in: V. Avila-Reese, C. Firmani, C. Frenk, & C. Allen (eds.), *Galaxy Evolution: Theory and Observations*, RevMexAA SC (*astro-ph/0310865*)

Inoue, A. K., Hirashita, H., & Kamaya, H. 2001, *ApJ*, 555, 613

Kim, K.-T., & Koo, B.-C. 2001, *ApJ*, 549, 979

Spitzer, L., Jr. 1978, *Physical Processes in the Interstellar Medium*, (New York: Wiley)

Thuan, T. X., Izotov, Y. I., & Lipovetsky, V. A. 1997, *ApJ*, 463, 120

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