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Neutral Hydrogen in M31. V. The Formation Rate of H II Regions and a Correction Factor for the Star Formation Rate

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Abstract

The relation among the densities of H II regions ($\rho_{\mathrm{H\,II}}$), young stars (ρ_*), and H I gas ($\rho_{\mathrm{H\,I}}$) in M31 is reexamined. We find a power-law relation among them as $\rho_{\mathrm{H\,II}}/\rho_*=\kappa\rho_{\mathrm{H\,I}}{}^m$, where κ is a constant and the value of index m is about 0.9. We point out that the "star formation rate" derived from the densities of H II regions and H I gas does not represent the true rate. The power index $n_{\mathrm{H\,II}}$ derived from H II regions ($\rho_{\mathrm{H\,II}}\propto\rho_{\mathrm{HI}}{}^{n_{\mathrm{H\,II}}}$) must be corrected for the excess m to obtain the power index n_* of star formation rate ($\rho_*\propto\rho_{\mathrm{H\,I}}{}^{n_*}$) as $n_*=n_{\mathrm{H\,II}}-m$. The value of n_* derived for several galaxies is 0.8 ± 0.1.

Key words: Galaxies; H II regions; M31; Neutral hydrogen; Star formation.

1. Introduction

The relation between the densities of population I objects (ρ_*) and H I gas ($\rho_{\mathrm{H\,I}}$) in galaxies has been well represented by a power-law relation,

$$\rho_*=\kappa\rho_{\mathrm{H\,I}}{}^n, \qquad (1)$$

where κ is a constant. If ρ_* is proportional to the rate of star formation, equation (1) shows a dependence of the rate of star formation on the gas density. Many authors have obtained the value of the power index n in our Galaxy and in some external galaxies, since Schmidt (1959) proposed the relation in this form. In those studies, however, H II regions have been frequently used to derive the relation (e.g. Hamajima and Tosa 1975) instead of young stars, because the detection of H II regions is easier even in distant galaxies compared to that of individual stars or star clusters. It has been believed that the power-law relation obtained for H II regions and the H I gas represents the rate of *star* formation.

In a previous paper [Nakai and Sofue (1982), hereafter referred to as Paper IV] we have investigated the relations of various optical features in M31 to the H I gas distribution

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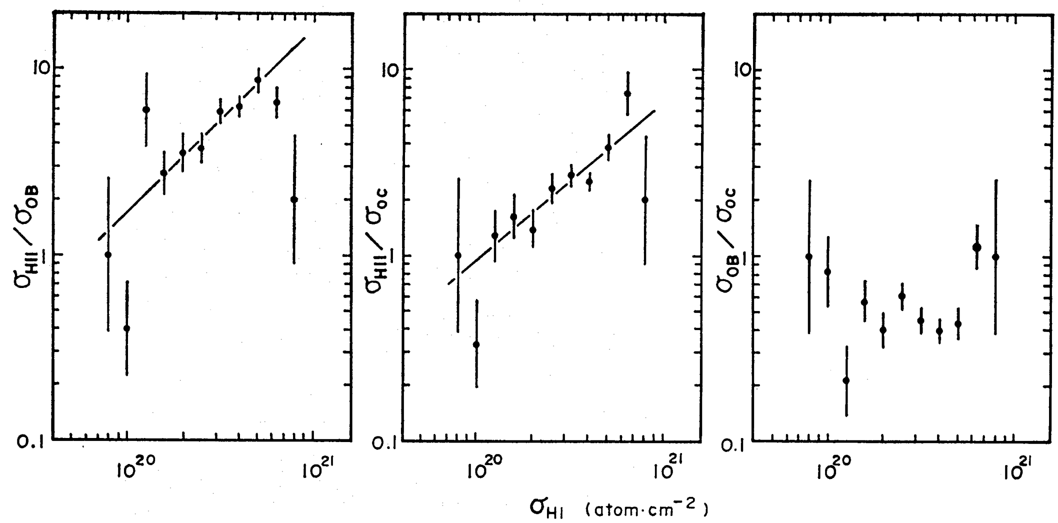

Fig. 1. The relations of σ_{HII}/σ_{OB}, σ_{HII}/σ_{oc}, and σ_{OB}/σ_{oc} to the surface number density of the H I gas σ_{HI} for $R<20$ kpc. The straight line shows the least-squares fit by a power-law relation.

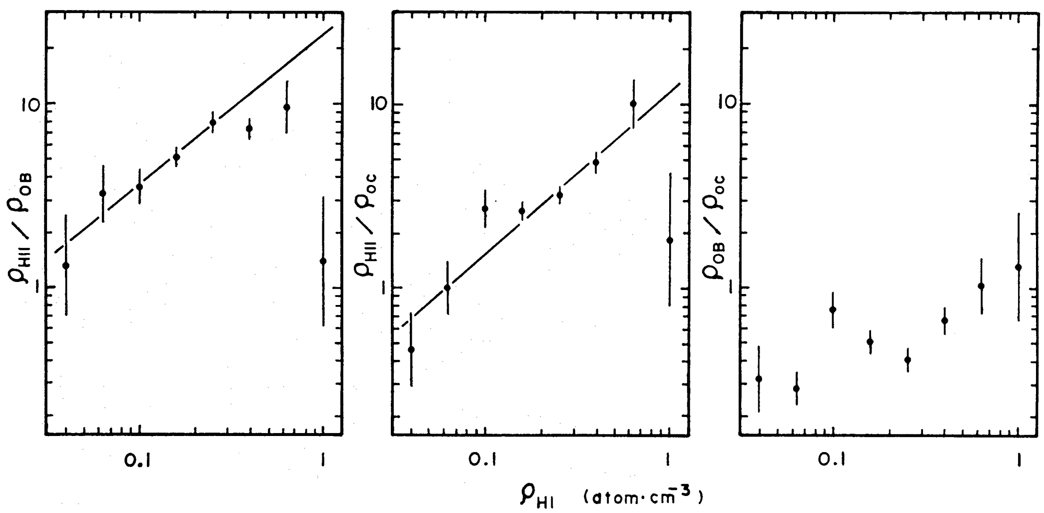

Fig. 2. The same relations as figure 1 but for the volume density.

derived by Sofue and Kato (1981, Paper I). We have pointed out that the value of the power-law index n determined from H II regions is greater than those determined from OB associations and open clusters.

In this paper we discuss implications of such a difference between the dependences of H II regions and young stars on the H I gas in M31. We point out that the value n obtained from H II regions does *not* give the real *star* formation rate but is overestimated.

2. Analysis and Results

Figure 1 shows logarithmic plots of the ratios of the surface number densities of H II regions ($\sigma_{H\,II}$), OB associations (σ_{OB}), and open clusters (σ_{oc}) to that of the H I gas ($\sigma_{H\,I}$) at galactocentric distances less than 20 kpc in M31. Figure 2 shows the same relations as in figure 1, but for the volume number densities. The volume densities were evaluated

Table 1. The power-law index n defined through $\sigma_{\mathrm{H\,II,OB,oc}} \propto \sigma_{\mathrm{H\,I}}{}^{n}$ and $\rho_{\mathrm{H\,II,OB,oc}} \propto \rho_{\mathrm{H\,I}}{}^{n}$ at $R<20$ kpc, where R is the galactocentric distance (after Paper IV).

Objects	n	
	Surface density	Volume density
H II regions	1.94±0.11	2.06±0.10
OB associations	0.81±0.12	1.38±0.11
Open clusters	0.99±0.12	1.30±0.08

Table 2. The power-law index m defined through $\sigma_{\mathrm{H\,II}}/\sigma_{\mathrm{OB,oc}} \propto \sigma_{\mathrm{H\,I}}{}^{m}$ and $\rho_{\mathrm{H\,II}}/\rho_{\mathrm{OB,oc}} \propto \rho_{\mathrm{H\,I}}{}^{m}$ at $R<20$ kpc.

Objects	m	
	Surface density	Volume density
H II regions/OB associations	0.99±0.21	0.81±0.19
H II regions/open clusters	0.86±0.16	0.88±0.12

by dividing the surface densities by the thickness of the galactic disk described in Paper IV. The above plots are based on the same data as those used in Paper IV, but are given to demonstrate in a more straightforward way to show how the ratios of the density of H II regions to young stars depend on the gas density.

The relation between log $\sigma_{\mathrm{H\,II}}/\sigma_{\mathrm{OB}}$ and log $\sigma_{\mathrm{H\,I}}$ and that between log $\sigma_{\mathrm{H\,II}}/\sigma_{\mathrm{oc}}$ and log $\sigma_{\mathrm{H\,I}}$ in figure 1 are well fitted by straight lines. In the case of the volume densities in figure 2, similar results are obtained. Therefore the densities of these objects are represented by simple power-law relations:

$$\sigma_{\mathrm{H\,II}}/\sigma_{*}=\kappa\sigma_{\mathrm{H\,I}}{}^{m} \tag{2}$$

and

$$\rho_{\mathrm{H\,II}}/\rho_{*}=\kappa\rho_{\mathrm{H\,I}}{}^{m}\,, \tag{3}$$

where σ_{*} and ρ_{*} are the surface and volume number densities of population I stellar objects (OB associations or open clusters), respectively, and κ and m are constants. Table 2 lists the best-fit values of m. The power-law index m should correspond to the difference between the value of n of H II regions and that of OB associations or open clusters. If we apply equation (1) to H II regions and stellar objects, then

$$\rho_{\mathrm{H\,II}}=\kappa'\rho_{\mathrm{H\,I}}{}^{n_{\mathrm{H\,II}}}\,,$$

and

$$\rho_{*}=\kappa''\rho_{\mathrm{H\,I}}{}^{n_{*}}\,.$$

Therefore we obtain

$$\rho_{\mathrm{H\,II}}/\rho_{*}=\kappa'''\rho_{\mathrm{H\,I}}{}^{n_{\mathrm{H\,II}}-n_{*}}\,. \tag{4}$$

Then from equations (3) and (4), we obtain the relation

$$m=n_{\mathrm{H\,II}}-n_{*}\,. \tag{5}$$

Table 3. The power-law index n in other galaxies.

Galaxy	Objects	n	$m = n_{\mathrm{H\,II}} - n_*$	Reference
M33	Bright young stars	2.09 ± 0.16	0.3 ± 0.3	Madore et al. (1974)
	H II regions	2.35 ± 0.26	—	Madore et al. (1974)
LMC	O–B2 supergiants	0.43 ± 0.17	1.5 ± 0.4	Martin et al. (1976)
	H II regions	1.9 ± 0.3	—	Tosa and Hamajima (1975)
SMC	Cepheids	1.66 ± 0.31	0.9 ± 0.4	van Genderen (1969)
	O–B supergiants ($m_{\mathrm{pg}} \leqq 12.9$)	1.84 ± 0.14	0.8 ± 0.3	Sanduleak (1969)
	O–B2 supergiants	2.18 ± 0.24	0.4 ± 0.4	Azzopardi and Vigneau (1977)
	All stars with $m_{\mathrm{pg}} < 16.0$	1.42 ± 0.02	1.2 ± 0.3	Azzopardi and Vigneau (1977)
	H II regions	2.6 ± 0.3	—	Hamajima and Tosa (1975)
	Mean		$\overline{m} = 0.8 \pm 0.1$	

The plot of $\sigma_{\mathrm{OB}}/\sigma_{\mathrm{oc}}$ against $\sigma_{\mathrm{H\,I}}$ in figure 1 shows no meaningful correlation. The plot of $\rho_{\mathrm{OB}}/\rho_{\mathrm{oc}}$ against $\rho_{\mathrm{H\,I}}$ in figure 2 seems to suggest a weak correlation. This correlation, if it is real, will be possibly due to the fact that OB associations are short-lived and generally younger than open clusters so that the open clusters may be distributed at longer distances from the galactic shock-compressed H I arms.

3. Discussion

(*i*) *Formation Rate of H II Regions*

OB associations are very young *stars*, and open clusters detected in M31 are also fairly young *stars* (10^6–10^8 yr) (Hodge 1979), while H II regions are *ionized gases* surrounding massive stars. Equations (2) and (3) show that the density of an ionized gas region is proportional to the density of exciting stars and the power of the density of the H I gas. This phenomenon probably arises from the fact that the formation of stars is affected by the gas density, while the formation of H II regions is affected not only by the ambient gas but also by exciting young stars. Even if the same number of OB stars are formed, the ionized gas surrounding the exciting stars in a region of lower gas density would be more easily evaporated by the UV photons from the stars. As a consequence the number of bright H II regions is smaller in regions of lower gas density than in regions of higher gas density. A theoretical investigation is needed to quantitatively understand this phenomenon.

(*ii*) *Other Galaxies*

Table 3 shows power-law relations between H I gas and population I objects in other galaxies in which stellar objects have been detected. The representative objects for young stars in table 3 are not always the same, so that the comparison of the power indices n is not straightforward. However, it is clear that the indices derived for H II regions are always larger than those derived for young stars in all the galaxies in table 3. The mean excess of $n_{\mathrm{H\,II}}$ for H II regions over n_* for population I stellar objects is $m = 0.8 \pm 0.1$, which is in good agreement with the value of m obtained for M31 (table 2). Therefore, it is likely that the value of m is universal and constant for any galaxy.

Table 4. The value of n_* in galaxies defined by $n_* \equiv n_{\rm H\,II} - m$, where $m = 0.9 \pm 0.1$.

Galaxy	n_*	Reference of $n_{\rm H\,II}$
NGC 224 (M31)	1.0 ± 0.2	(1)
NGC 598 (M33)	1.5 ± 0.3	(2)
NGC 2403	2.0 ± 0.3	(3)
NGC 3031 (M81)*	0.4 ± 0.1	(5)
NGC 3359*	1.3 ± 0.6	(5)
NGC 5194 (M51)	0.9 ± 0.4	(3)
NGC 5457 (M101)	0.6 ± 0.6	(3)
NGC 6946	1.1 ± 0.7	(3)
LMC	1.0 ± 0.3	(4)
SMC	1.7 ± 0.3	(3)

* $n_{\rm H\,II}$ for NGC 3031 and NGC 3359 are 1.3 ± 0.1 and 2.2 ± 0.6, respectively.

References: (1) Nakai and Sofue (1982). (2) Madore et al. (1974). (3) Hamajima and Tosa (1975). (4) Tosa and Hamajima (1975). (5) This paper.

The data of H II regions and H I gas are taken from the following references:

Galaxy	H II regions	H I gas
NGC 3031	Hodge and Kennicutt (1983)	Rots and Shane (1975)
NGC 3359	Hodge (1969)	Gottesman (1982)

(*iii*) *Correction Factor m for the Power-Law Index of Star Formation Rate*

Detection of individual stars or star clusters is usually difficult in more distant galaxies than M31 and galaxies listed in table 3. Therefore, the dependence of the star formation rate on the gas density has been obtained so far using only H II regions. The power-law indices $n_{\rm H\,II}$ evaluated in this way, however, are overestimated and the "correction factor" m must be subtracted from $n_{\rm H\,II}$ to get the power indices n_* for the "true" star formation rate. Table 4 shows the value of n_*, defined by $n_* \equiv n_{\rm H\,II} - m$, for the surface density derived for several galaxies. Here we used the value of m obtained for M31 and galaxies in table 3; $m = 0.9 \pm 0.1$. The mean value of derived n_* is 0.8 ± 0.1. It is therefore likely that the formation rate of massive stars is proportional to the first power of the H I gas for the majority of galaxies.

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