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GIANT HII REGIONS AS DISTANCE INDICATORS

Jorge Melnick*)
European Southern Observatory

Roberto Terlevich
Royal Greenwich Observatory

Mariano Moles
Observatorio Astronómico Nacional de España, and
Instituto de Astrofísica de Andalucía

RESUMEN. Se muestra que las correlaciones entre la luminosidad Hβ, el ancho del perfíl de las líneas de emisión y la abundancia de oxígeno que se observa en regiones HII gigantes y galaxias HII provee un poderoso método para determinar distancias a estos objetos. El método es calibrado usando regiones HII en galaxias de distancias conocidas y se aplica a la determinación de distancias a galaxias HII lejanas. De aquí se obtiene un valor de H_o = 95±10 km/sec/Mpc para la constante de Hubble, valor que está en excelente acuerdo con el que se obtiene a partir de la relación de Tully-Fisher usando la misma calibración local. Se discuten posibles efectos sistemáticos que podrían complicar el uso de regiones HII como indicadores de distancias a galaxias muy lejanas.

ABSTRACT. The correlations between the integrated Hβ luminosities, the velocity widths of the nebular lines and the metallicities of giant HII regions and HII galaxies are demonstrated to provide powerful distance indicators. They are calibrated on a homogeneous sample of giant HII regions with well determined distances and applied to distant HII galaxies to obtain a value of H_o = 95±10 for the Hubble parameter, consistent with the value obtained by the Tully-Fisher technique. The effect of Malmquist bias and other systematic effects on the HII region method are discussed in detail.

Key words: DISTANCES — GALAXIES-IRREGULAR — NEBULAE-H II REGIONS

I. INTRODUCTION

The largest giant HII regions in late type galaxies have traditionally played an important role in the calibration of the extragalactic distance scale owing to the existence of an empirical correlation between their linear diameters and the luminosity of their parent galaxies (Sersic, 1960; Sandage and Tammann, 1974; van den Bergh, 1980; Teerikorpi, 1985).

Melnick (1978) showed that the diameters of giant HII regions are well correlated with their integrated emission line velocity widths and, therefore, that the correlation between these line widths and parent galaxy luminosity provides a powerful distance indicator which is free of some of the shortcomings affecting the Sersic-Sandage method.

Perhaps the most useful application of giant HII regions to the determination of distances was proposed by Terlevich and Melnick (1981) who showed that the integrated Hβ luminosities, L(Hβ), of giant HII regions are very well correlated with their emission-line velocity widths, σ.

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*) On leave from Astronomy Department, Universidad de Chile

In this contribution we review this property of giant HII regions as distance indicators based on a new set of homogeneous observations for a sample of giant HII regions in nearby galaxies with accurately known distances and we apply these results to a sample of distant HII galaxies to derive a "global" value for the Hubble parameter.

II. GIANT HII REGIONS AS DISTANCE INDICATORS

Here we present a brief summary of the global properties of giant HII regions based on the recent review by Melnick et al. (1986, MMTG) to which we refer fcr further details. Briefly, the study of MMTG is based on new data for 22 giant HII regions for which Sandage and Tammann (1974) give diameters and distances. MMTG adopted the distance scale used by Aaronson et al. (1986) in their calibration of the IR Tully-Fisher relation which, with the exception of M33, NGC 6822, and the SMC, is equivalent to the calibration adopted by Sandage and Tammann (1974; 1982). Table 1 lists the galaxies used by MMTG and their distance moduli. Also given are the distances used by Sandage and Tammann (ST82).

TABLE 1. Distance Modulii to the Zero Point Calibrators

Parent galaxy	Number of HII regions	$(m-M)_0$ MMTG	ST82
LMC	1	18.50	18.59
SMC	1	18.89	19.27
NGC 6822	2	23.3	23.95
M33	4	24.17	24.56
NGC 2366	3	27.5	27.56
NGC 2403	3	27.5	27.56
Holmberg II	1	27.5	27.56
IC 2574	2	27.5	27.56
NGC 4236	2	27.5	27.56
M101	3	29.2	29.2

Figure 1 presents a logarithmic plot of the integrated Hβ luminosity of giant HII regions corrected for internal and foreground extinction, L(Hβ), as a function of the rms velocity width of their emission line profiles, σ, determined from large aperture Fabry-Perot interferometry.

The line shows a least-squares fit to the data of the functional form,

$$\log L(H\beta) = (4.2\pm0.5) \log \sigma + (34.12\pm0.56) \quad \text{eq. 1}$$

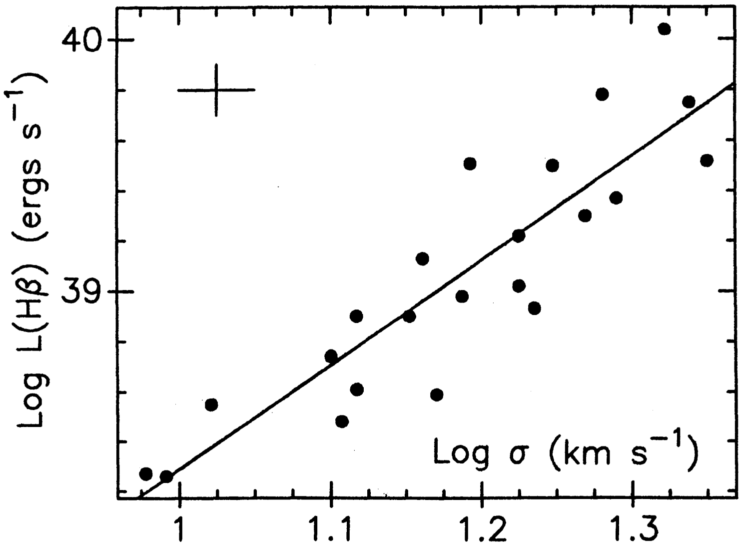

Figure 1: Correlation between integrated Hβ luminosity and velocity dispersion for giant HII regions.

The rms scatter about this line is $\delta \log L(H\beta) = 0.23$ (e.g. $\delta M = 0^{m}\!.57$) which is comparable to the scatter of the infrared Tully-Fisher relation, $\delta M = 0^{m}\!.45$, considered one of the best available distance indicators (Aaronson et al., 1986 and references therein). The scatter in the $(L(H\beta),\sigma)$ relation, however, is partly real and due to an abundance effect. Using Principal Component Analysis (PCA) techniques, MMTG found that the Hβ luminosity correlates very tightly with the parameter,

$$Mz = \frac{R_c \sigma^2}{(O/H)}$$

where R_c is the core radius and O/H the oxygen abundance of the HII regions. The scatter in the $(L(H\beta),Mz)$ relation is somewhat smaller, but this advantage to determine distances is offset by the uncertainties in the abundances and core radii which are observationally considerably more difficult to obtain than luminosities and emission line widths. Nevertheless, HII galaxies are systematically metal poor relative to giant HII regions (in fact this is one of their defining properties) and therefore the metallicity dependence must be taken into account in the calibration of the giant HII region correlations as distance indicators.

III. APPLICATION TO HII GALAXIES

HII galaxies are a class of dwarf irregular galaxies characterized by having a young stellar component that completely dominates their integrated spectrum at virtually all observable wavebands (Melnick, Terlevich and Eggleton, 1985; Melnick, Moles and Terlevich, 1985 and references therein).

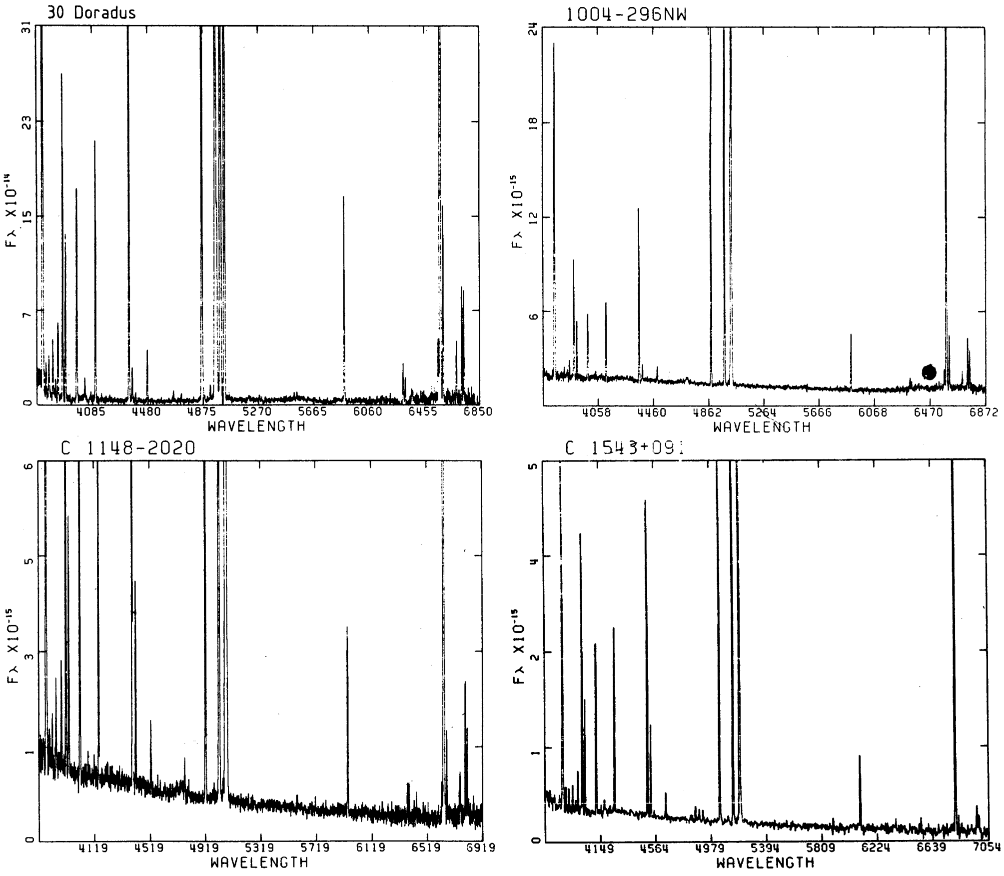

Figure 2: Spectra of 3 representative HII galaxies compared with the spectrum of the prototypical giant HII region 30 Doradus.

The optical spectra of HII galaxies resemble very closely those of typical giant HII regions. This is illustrated in Figure 2 where the spectra of several HII galaxies are compared to the spectrum of the prototypical giant HII region 30 Doradus. An important difference between HII galaxies and giant HII regions is that HII galaxies are, on the average, significantly more metal deficient. This difference reflects the fact that HII galaxies are in general dwarf systems; the masses of HII galaxies estimated from their velocity dispersions range between 10^7 and 10^{10} $M_{\odot}$ but these are the masses of the young component only. Viewed in deep CCD pictures, some HII galaxies exhibit extended low surface brightness components while others show essentially stellar morphology.

Terlevich et al. (1986) have compiled a spectrophotometric catalogue of about 450 HII galaxies. We have obtained Echelle spectra for 60 of these galaxies out of which for 41 we have accurate Hβ fluxes and for 25 we have both fluxes and oxygen abundances. We will present here the analysis of these observations; the observational details will be presented elsewhere (Melnick, Terlevich and Moles, 1986; hereafter MTM).

Figure 3 presents a logarithmic plot of L(Hβ) versus σ for our 41 HII galaxies. A Hubble constant of 100 km/sec/Mpc has been used to compute the distances. The radial velocities have been corrected for the motion of the sun relative to the centre of the local group using the standard IAU formula (V_0 = 300cosA) for the motion of the local group relative to Virgo using solution Case 6 of Aaronson et al. (1986) and for the perturbation of the Hubble flow by the Virgo cluster using the linear model of Aaronson et al. (1982). The HII galaxies in Virgo itself have been assigned a kinematical distance of 1080 km/sec following Aaronson et al. (1986). No corrections have been applied to account for the motion of the local group relative to the cosmic microwave background (see contribution by Melnick and Moles in this volume). The solid line shows a least squares fit to the data of slope 4.7±0.3. As expected from the results of MMTG, the residuals in this correlation depend on oxygen abundance. A principal component analysis gives,

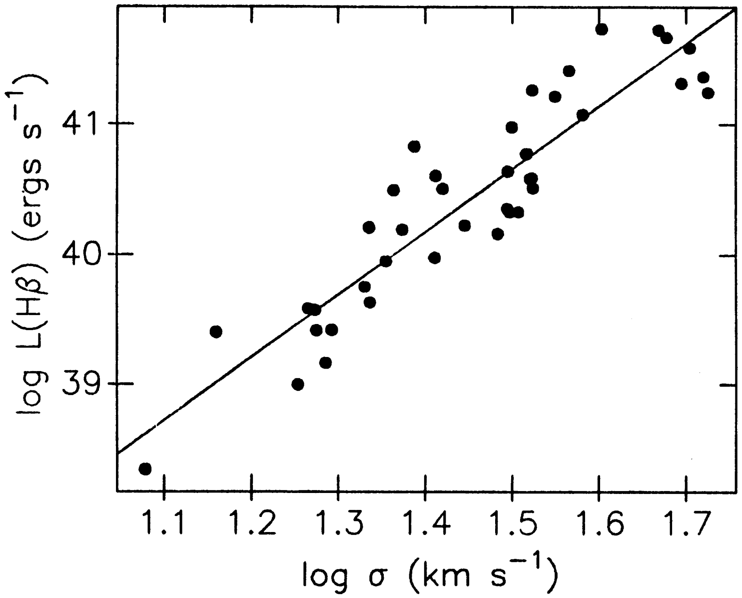

Figure 3: Correlation between Hβ luminosity and velocity dispersion for HII galaxies. The line shows a least squares fit of slope 4.7.

$$\log L(H\beta) = 5.0 \log \sigma - 1.0 \log (O/H) + \text{constant} .$$

We lack radii for HII galaxies so a proper comparison with giant HII regions cannot be made but the results are entirely consistent since for giant HII regions $R_c \sim \sigma^3$ (MMTG). In fact if $R_c\sigma^2$ is replaced by σ^5 the eigenvectors and eigenvalues for HII galaxies are identical to those obtained by MMTG for giant HII regions (MTM). This leads us to conclude that the Hβ luminosities of HII galaxies are entirely determined by two parameters (σ and O/H) and that (the young component of) HII galaxies are gravitationally bound clusters of gas fragments ionized by a coeval stellar population of variable IMF (Terlevich and Melnick, 1981, 1983; MTM). This conclusion is supported by a number of independent arguments based on the spectral properties of HII galaxies (Terlevich, 1985).

For a given mass ($R\sigma^2$) and metallicity, age differences will introduce significant scatter in the Hβ luminosities of HII regions (Copetti et al., 1986). In principle it should be possible to correct for this effect using the equivalent width of Hβ (W(Hβ)) as the age parameter (Copetti et al., 1986). In practice, however, integrated equivalent widths for giant HII regions are difficult to obtain and are not available. Thus, in order to minimize the scatter of ages we will only consider giant HII regions and HII galaxies of integrated equivalent widths greater than 30 Å. This limits our sample to objects younger than about 4 million years.

Figure 4 presents a plot of L(Hβ) versus $Mz = \sigma^5/(O/H)$. The slope of this relation is 1.01±0.06, the rms scatter is $\delta \log L(H\beta) = 0.21$ and the correlation coefficient is $r = 0.97$.

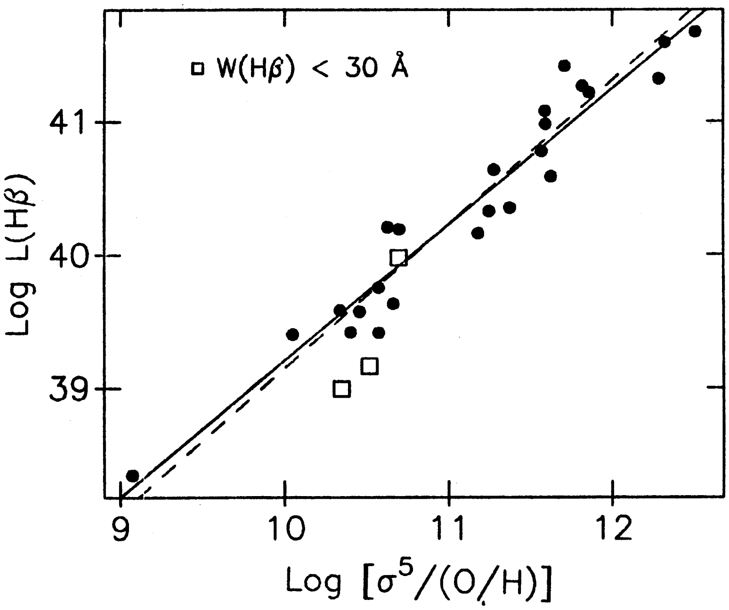

Figure 4: Correlation between Hβ luminosity and the distance indicator parameter $Mz = \sigma^5/(O/H)$. The lines represent the least squares (solid) and maximum-likelihood (dashed) fits to the data.

The scatter of this relation is consistent with the observational errors and therefore we may assume that there is a physical relation between L(Hβ) and Mz. In this case, maximum likelihood (M-L) techniques may be used to determine the slope of this relation (MMTG) and this is shown by the dashed line (slope = 1.08±0.04).

IV. THE HUBBLE PARAMETER H_0

The systematic difference in the mean metallicities of HII regions and HII galaxies force us to use the (L(Hβ),Mz) relation as distance indicator and therefore to use only giant HII regions and HII galaxies with accurate metallicities. Only 14 of the 22 giant HII regions in the sample of MMTG have metallicities and therefore the slope of the correlation cannot be reliably determined from these data (MTM). Our HII galaxies sample, on the other hand, is affected by Malmquist bias which leads us to overestimate both the slope of the correlation and the luminosities of the most distant objects. Therefore in order to determine the slope of the (L(Hβ),Mz) relation we must correct for this effect or at least assess its importance. The effect of Malmquist bias in our correlations is similar to its effect on the Tully-Fisher relation which has been extensively discussed in the literature (see e.g. Giraud, 1986 and references therein). In particular, Teerikorpi (1984) gives detailed equations to correct magnitude limited samples for Malmquist bias. We have used Teerikorpi's equations to estimate the effect of Malmquist bias on the slopes of the corrections and to correct our estimates of H_0 for bias.

After bias-correction we find a slope of 4.5±0.3 for the (L(Hβ),σ) relation and slopes of 0.98±0.05 (least-squares) and 1.03±0.04 (M-L) for the (L(Hβ),Mz) relation (the uncorrected slopes are 4.7±0.3, 1.01±0.05 and 1.06±0.04). The slopes determined on the giant HII region sample are 4.2±0.5, 0.83±0.13 and 1.02±0.08. Thus the effect of Malmquist bias on the slope of the (L(Hβ),Mz) relation is only marginal. This is because the scatter of the relation is small while the sample spans a large range in luminosity. We will therefore adopt a slope of 1.0 for the relation. For this slope the zero point obtained from the giant HII regions is 29.32±0.28.

Neglecting deceleration effects H_0 is obtained as (Sandage, 1975),

$$\langle H_0 \rangle = \frac{1}{N} \sum_{i=1}^{N} \left[\frac{L_i(\sigma,O/H)}{4\pi \ell_i (1+z_i)^2} \right]^{1/2} (cz_i)^{-1}$$

where ℓ_i are the observed Hβ fluxes, $L_i(\sigma, O/H)$ the Hβ luminosities obtained from the velocity dispersions and oxygen abundances and z_i the (corrected) redshifts. Table 2 summarizes the results we obtain for different redshift ranges and the result from the (L(Hβ),σ) relation (Eq. 1). The corrections for Malmquist bias are given in this table as δH_0. The errors are rms deviations from the mean of the HII galaxies used (N) and do not include the errors in the zero point calibrations.

TABLE 2. The Hubble parameter

	$\langle H_0 \rangle$	δH_0	N
	km s^{-1}	Mpc^{-1}	
a) Using (L(Hβ),Mz):			
full sample :	94±5	6	25
cz > 2000 km s :	100±7	2	16
out of Virgo :	97±6	2	19
b) Using (L(Hβ),σ):			
full sample :	154±10	17	42
with known O/H :	137±9	14	25

The discrepancy between both sets of results given in Table 2 reflects the systematic differences in metallicity between the calibrators and the HII galaxies. There are 14 giant HII regions in the MMTG sample with reliable metallicities. The mean oxygen abundance of these nebulae is 12+log(O/H) = 8.173. If we restrict the application of the (L(Hβ),σ) relation to HII galaxies with known abundances (Table 2) we find a mean abundance of 12+log(O/H) = 8.054. Since the luminosities scale linearly with (O/H) for a given velocity dispersion, HII galaxies will, on the average, be more luminous than giant HII regions by a factor <δlogL(Hβ)> = 8.173-8.054. Correcting for this effect we obtain H_0 = 93±9 km/sec/Mpc from the (L(Hβ),σ) relation consistent with the result from the (L(Hβ,Mz) method (Table 2).

V. DISCUSSION

We have listed in Table 2 the results for three different redshift cuts of our sample. Clearly, the result for cz > 2000 km/sec should be closest to the "global" value of H_0 but it is based on a smaller number of objects. Thus, we will adopt the result excluding the 5 galaxies in Virgo, H_0 = 97±6 km s^{-1} Mpc^{-1}.

Including the uncertainty in the zero point calibration, our best estimate of the Hubble constant, after correction for Malmquist bias, is H_0 = 95±10 km s^{-1} Mpc^{-1}. This is in excellent agreement with the value H_0 = 92±1 km/sec/Mpc obtained by Aaronson et al. (1986) from the IR Tully-Fisher relation. The agreement is very rewarding because, since we have used the same local distance scale as Aaronson et al., it means that there are no systematic errors in our zero point calibration. The value we obtained using the local distance scale of ST82 is H_0 = 87±10. From the 5 galaxies in Virgo we obtain a true distance modulus of $(m-M)_{vir}$ = 30.79±0.25 for the cluster again in very good agreement with the value of $(m-M)_{vir}$ =

30.82±0.12 found by Aaronson et al. (1986).

A potentially serious difficulty with HII regions arises from confusion; from the Spectrophotometric Catalogue of HII Galaxies (Terlevich et al., 1986) we know that an important fraction of HII galaxies are multiple, e.g. are dwarf-irregular galaxies with more than one large burst of star formation. Clearly, if several giant HII regions of a distant galaxy fall in the spectrograph slit we will get too large a flux for the velocity dispersion, if they are at the same radial velocity, or too large velocity dispersion for the flux if the parent galaxy rotates fast and in general a combination of both effects. In principle, one could discriminate rotation by eliminating galaxies with non-gaussian profiles but in practice the profiles may be "almost" gaussian and impossible to distinguish objectively from "true" gaussians. In the present analysis we have eliminated all HII galaxies with velocity dispersion larger than 60 km/sec. This value is obtained if the free-fall time for the ionizing clusters is equal to the "useful" lifetime of a massive star - about 4-5 million years. It is clear, however, that while this cutoff may effectively eliminate all HII galaxies severely affected by rotation, it will not discriminate against multiple objects with similar radial velocities.

The low scatter we find in the HII galaxy correlations guarantees that contamination is not severe for our present sample but it may clearly hamper the application of HII regions to the determination of distances to HII galaxies at cosmological distances.

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Jorge Melnick: Depto. de Astronomía, Universidad de Chile, Casilla 36-D, Santiago de Chile.
Mariano Moles: Instituto de Astrofísica de Andalucía, Apartado Postal 2144, Granada, Spain.
Roberto Terlevich: Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, East Sussex BN27 1RP, England.