

# Determining the Hubble constant using giant extragalactic H II regions and H II galaxies

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Accepted 2012 June 8. Received 2012 June 8; in original form 2012 March 28

## ABSTRACT

We report the first results of a long-term programme aiming to provide accurate independent estimates of the Hubble constant ( $H_0$ ) using the  $L(\text{H}\beta)$ – $\sigma$  distance estimator for giant extragalactic H II regions (GEHR) and H II galaxies.

We have used Very Large Telescope and Subaru high-dispersion spectroscopic observations of a local sample of H II galaxies, identified in the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) catalogue in order to redefine and improve the  $L(\text{H}\beta)$ – $\sigma$  distance indicator and to determine the Hubble constant. To this end, we utilized as local calibration or ‘anchor’ of this correlation GEHR in nearby galaxies which have accurate distance measurements determined via primary indicators. Using our best sample of 69 nearby H II galaxies and 23 GEHR in nine galaxies, we obtain  $H_0 = 74.3 \pm 3.1$  (statistical)  $\pm 2.9$  (systematic)  $\text{km s}^{-1} \text{Mpc}^{-1}$ , in excellent agreement with, and independently confirming, the most recent Type Ia supernovae based results.

**Key words:** H II regions – cosmological parameters – distance scale.

## 1 INTRODUCTION

The accurate determination of the Hubble constant,  $H_0$ , is considered one of the most fundamental tasks in the interface between astronomy and cosmology. The importance of measuring the expansion rate of the Universe to high precision stems from the fact that  $H_0$ , besides providing cosmic distances, is also a prerequisite for independent constraints on the mass-energy content of the Universe (e.g. Suyu et al. 2012).

The direct determination of the Hubble constant can only be obtained by measuring cosmic distances and mapping the local expansion of the Universe, since the Hubble relation,  $cz = H_0 d$ , is valid and independent of the mass-energy content of the Universe only locally ( $z \lesssim 0.15$ ). A variety of methods have been used to estimate  $H_0$ , based on Cepheids, surface brightness fluctuations, masers, the tip of the red giant branch (TRGB) or Type Ia supernovae (SNe Ia; for general reviews, see Jackson 2007; Tammann, Sandage & Reindl 2008; Freedman & Madore 2010). In particular, the use of SNe Ia

to measure the Hubble constant has a long history in astronomy (e.g. Sandage & Tammann 1982, 1990). The subsequent discovery of the correlation between the magnitude at peak brightness and the rate at which it declines thereafter (e.g. Phillips 1993) allowed the reduction of the distance determination intrinsic scatter. However, one has to remember that SNe Ia are secondary indicators and their use relies on the determination of well-established local calibrators, such as the Large Magellanic Cloud (LMC), Galactic Cepheids and the ‘maser’ galaxy NGC 4258 (cf. Riess et al. 2011).

Indirect methods to measure  $H_0$  have also been developed (e.g. Bonamente et al. 2006; Suyu et al. 2010; Beutler et al. 2011); however, all of the indirect methods use as priors other cosmological parameters, and thus the resulting  $H_0$  determinations are model dependent.

Returning to the direct method to estimate  $H_0$ , an important breakthrough occurred a decade or so ago by the *Hubble Space Telescope* (HST) Calibration programme (Saha et al. 2001; Sandage et al. 2006), which found Cepheids in local galaxies that host SNe Ia and provided a Cepheid-based zero-point calibration, and by the HST Key project (Freedman et al. 2001), which furnished a value of  $H_0 = 72 \pm 2$  (random)  $\pm 7$  (systematic)  $\text{km s}^{-1} \text{Mpc}^{-1}$ , based on Cepheid distances of external galaxies and the LMC as the first rung

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of the distance ladder. This value was recently revised by the same authors, using a new Cepheid zero-point (Benedict et al. 2007) and the new SNe Ia of Hicken et al. (2009), to a similar but less uncertain value of  $H_0 = 73 \pm 2$  (random)  $\pm 4$  (systematic)  $\text{km s}^{-1} \text{Mpc}^{-1}$  (see Freedman & Madore 2010). Tammann et al. (2008) used a variety of local calibrators to recalibrate the SNe Ia and found a significantly lower value of  $H_0 = 62.3 \pm 4 \text{ km s}^{-1} \text{Mpc}^{-1}$ . The difference has since been explained as being due to a variety of external causes, among which are the use of heavily reddened Galactic Cepheids and of less accurate photographic data (Riess et al. 2009a,b).

The most recent analysis of Riess et al. (2011) uses new *HST* optical and infrared observations of 600 Cepheid variables to determine the distance to eight galaxies hosting recent SNe Ia. The resulting best estimate for the Hubble constant is  $H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{Mpc}^{-1}$  including random and systematic errors.

From the above discussion, it becomes clear that SNe Ia are the only tracers of the Hubble expansion utilized to date, over a relatively wide redshift range ( $0 \lesssim z \lesssim 1.5$ ). Therefore, due to the great importance of direct determinations of the Hubble constant for cosmological studies (e.g. Suyu et al. 2012), it is highly desirable to independently confirm the SNe Ia-based  $H_0$  value by using an alternative tracer.

H II galaxies have been proposed as such an alternative. They are massive and compact (in many cases unresolved) bursts of star formation in dwarf galaxies. The luminosity of H II galaxies is completely overpowered by that of the starburst. As a consequence, they show the spectrum of a young H II region, which indeed is what they are, hence their name. Their similarity with giant extragalactic H II regions (GEHR) is underlined by the fact that the first examples of prototype H II galaxies, I Zw18 and II Zw40, were called ‘isolated extragalactic H II regions’ and found to be observationally indistinguishable from GEHR in nearby galaxies (Sargent & Searle 1970). They are discovered mainly in spectroscopic surveys due to their strong narrow emission lines, i.e. very large equivalent widths.

It is important to emphasize that the optical properties of H II galaxies are those of the young burst with almost no information (or contamination) from the parent galaxy. This is a direct consequence of selecting H II galaxies as those systems with the largest equivalent width ( $W$ ) in their emission lines, i.e.  $W(\text{H}\beta) > 50 \text{ \AA}$ .

Because the starburst component can reach very high luminosity, H II galaxies can be observed at large redshifts ( $z > 3$ ). What makes these galaxies interesting as cosmological distance probes (cf. Melnick, Terlevich & Terlevich 2000; Siegel et al. 2005) is the fact that as the mass of the starburst component increases, both the number of ionizing photons and the turbulent velocity of the gas, which is dominated by the star and gas gravitational potential, also increase. This induces a correlation between the luminosity of recombination lines, e.g.  $L(\text{H}\beta)$ , and the ionized gas velocity dispersion  $\sigma$  (see Terlevich & Melnick 1981; Hippelein 1986; Melnick, Terlevich & Moles 1988; Fuentes-Masip et al. 2000; Melnick et al. 2000; Telles, Muñoz-Tuñón & Tenorio-Tagle 2001; Bosch, Terlevich & Terlevich 2002; Siegel et al. 2005; Bordalo & Telles 2011).

A first attempt to estimate  $H_0$ , using H II galaxies and GEHR as local calibrators, was presented in Melnick et al. (1988). The use of H II galaxies as deep cosmological tracers was discussed by Melnick et al. (2000) and Siegel et al. (2005). Recently, we presented a thorough investigation of the viability of using H II galaxies to constrain the dark energy equation of state, accounting also for the effects of gravitational lensing, which are expected to be non-negligible for very high redshift ‘standard candles’ and we showed that indeed H II galaxies can provide an important cosmological probe (Plionis et al. 2011).

The aim of the current Letter is to use H II galaxies and a local calibration of the  $L(\text{H}\beta)$ – $\sigma$  relation based on GEHR of nearby galaxies, as an alternative direct approach for estimating the Hubble constant over a redshift range of  $0.01 < z < 0.16$ .

## 2 SAMPLE SELECTION AND OBSERVATIONS

A sample of 128 H II galaxies was selected from the SDSS DR7 spectroscopic data release (Abazajian et al. 2009) within a redshift range  $0.01 < z < 0.16$ , chosen for being compact ( $D < 5 \text{ arcsec}$ ), having large Balmer emission line fluxes and equivalent widths. A lower limit for the equivalent width of  $\text{H}\beta$  of  $50 \text{ \AA}$  was chosen to avoid starbursts that are either evolved or contaminated by an underlying older stellar population component (cf. Melnick et al. 2000). The redshift lower limit was chosen to minimize the effects of local peculiar motions relative to the Hubble flow and the upper limit to minimize any possible Malmquist bias and to avoid gross cosmological effects.

In order to improve the parameters of the  $L(\text{H}\beta)$ – $\sigma$  relation obtained from previous work, high-resolution echelle spectroscopy for the H II galaxy sample was performed at 8-m class telescopes. We used the Ultraviolet and Visual Echelle Spectrograph (UVES; Dekker et al. 2000) at the European Southern Observatory Very Large Telescope (VLT) in Chile and the High Dispersion Spectrograph (HDS; Noguchi et al. 2002; Sato et al. 2002) at the National Astronomical Observatory of Japan Subaru Telescope on Mauna Kea, Hawaii. The chosen set-ups provided UVES spectra centred at  $5800 \text{ \AA}$  with a slit width of  $2 \text{ arcsec}$ , giving a spectral resolution of  $\sim 22\,000$ . The HDS spectra were centred at  $\sim 5400 \text{ \AA}$ , and with a slit width of  $4 \text{ arcsec}$  the spectral resolution obtained was  $\sim 9000$ .

To obtain accurate total  $\text{H}\beta$  fluxes for the H II galaxy sample, we performed long-slit spectrophotometry at 2-m class telescopes under photometric conditions and using a slit width ( $8 \text{ arcsec}$ ) larger than the upper limit of the H II galaxies size in our sample. We used the Boller and Chivens spectrographs at the 2.1-m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir and at the 2.1-m telescope of the Observatorio Astrofísico Guillermo Haro in Cananea, both in Mexico.

Full details of the sample selection, observations and data reduction and analysis are given elsewhere (Chávez et al., in preparation). Here we summarize the relevant results regarding the determination of the distance estimator and  $H_0$ .

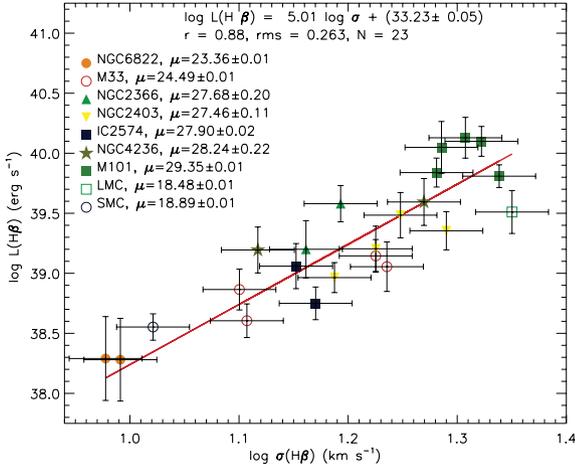
$\text{H}\beta$  and  $[\text{O III}] \lambda\lambda 4959, 5007$  line widths were measured by fitting single Gaussians to the line profiles. As previously found, most H II galaxies show line profiles that are well fitted by single Gaussians (e.g. Melnick et al. 1988; Bordalo & Telles 2011). We cleaned the sample by first removing from the original list those H II galaxies with either asymmetric or double/multiple line profile. We also removed those H II galaxies showing rotation or large photometric errors in their  $\text{H}\beta$  fluxes or with an uncertain reddening correction. It reduced the sample from 128 to 69 H II galaxies.

The values of the observed velocity dispersions,  $\sigma_o$ , were corrected for thermal ( $\sigma_t$ ) and instrumental ( $\sigma_i$ ) broadening, and the final corrected dispersion was estimated according to

$$\sigma = (\sigma_o^2 - \sigma_t^2 - \sigma_i^2)^{1/2}. \quad (1)$$

The  $1\sigma$  uncertainties of the velocity dispersion were estimated from multiple observations computing the variance over the repeated measurements, or as the mean value of the obtained relative errors.

$\text{H}\beta$  integrated fluxes were measured by fitting a single Gaussian to the long-slit spectra, while their  $1\sigma$  uncertainties were estimated



**Figure 1.**  $L(\text{H}\beta)$ – $\sigma$  relation for the GEHR sample. The correlation parameters and the adopted individual distance moduli are given in the inset. The line is the best fit for the slope determined by the fit to the H II galaxies (see equation 3).

from the expression (e.g. Tresse et al. 1999)

$$\sigma_F = \sigma_c D(2N_{\text{pix}} + W/D)^{1/2}, \quad (2)$$

where  $\sigma_c$  is the mean standard deviation per pixel of the continuum on each side of the line,  $D$  is the spectral dispersion,  $N_{\text{pix}}$  is the number of pixels covered by the line and  $W$  is the line equivalent width.

Heliocentric redshifts and their uncertainties were obtained from the SDSS DR7 spectroscopic data when available, otherwise from our echelle data or the spectrophotometric catalogue of H II galaxies (Terlevich et al. 1991). The redshifts have been transformed from the heliocentric to the Local Group reference frames following Courteau & van den Bergh (1999) and corrected for the local bulk flow using the model of Basilakos & Plionis (1998). The  $1\sigma$  uncertainties were propagated using a Monte Carlo procedure.

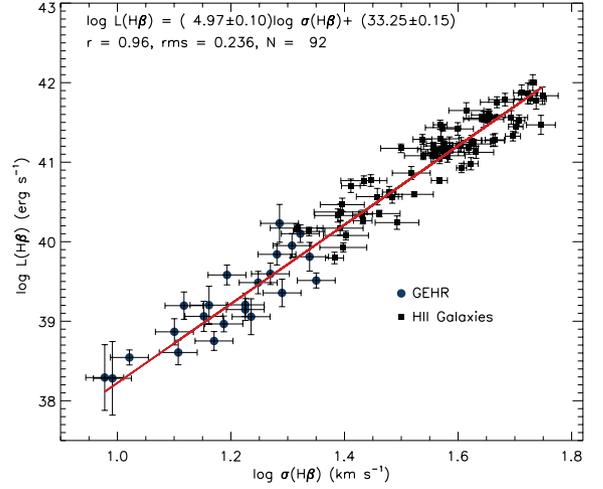
To determine the zero-point for the  $L(\text{H}\beta)$ – $\sigma$  relation, we obtained data from the literature for a sample of 23 GEHR in nine nearby galaxies whose distances have been measured by means of well-tested primary distance indicators.

The details of the GEHR data will also be given in Chávez et al. (in preparation). For these objects, velocity dispersions have been taken from Melnick et al. (1987), whereas distance moduli have been obtained by averaging over the available measurements published after 1995, selecting only those based on Cepheids, RR Lyrae, Mira variables and eclipsing binaries except for those in IC 2574 and NGC 4236 for which only TRGB measurements are available. The adopted distance moduli ( $\mu$ ) are listed as an inset in Fig. 1. The global integrated H $\beta$  fluxes and corresponding extinction were obtained from the values reported by Melnick et al. (1987).

### 3 DETERMINATION OF $H_0$

The procedure we use to estimate the Hubble constant comprises the following three steps.

(i) First we determine the slope of the  $L(\text{H}\beta)$ – $\sigma$  relation for H II galaxies. Since the slope is independent of  $H_0$ , we use an arbitrary



**Figure 2.**  $L(\text{H}\beta)$ – $\sigma$  relation for the joint H II galaxies and GEHR samples. The least-square fit considers the errors in both axes.

value of  $H_0$  to determine luminosities from the observed H $\beta$  flux and the Hubble distance.<sup>1</sup>

(ii) We then determine the intercept of the relation from a fit to the ‘anchor’ GEHR sample, but fixing the slope to that determined in step (i), i.e. that based on H II galaxies. Fig. 1 shows the  $L(\text{H}\beta)$ – $\sigma$  relation for the GEHR sample. The slope of the correlation has been fixed to the value obtained from the H II galaxies sample fitting in (i).

The resulting  $L(\text{H}\beta)$ – $\sigma$  correlation for the joint sample of GEHR and H II galaxies is

$$\log_{10} L(\text{H}\beta) = (4.97 \pm 0.10) \log_{10} \sigma + (33.25 \pm 0.15), \quad (3)$$

which has rms of  $\log_{10} L(\text{H}\beta) = 0.236$  (shown in Fig. 2).

(iii) Finally, we determine the value of  $H_0$  by minimizing, over a grid of  $H_0$  values, the function

$$\chi^2(H_0) = \sum_{i=1}^n \frac{[L_i(\sigma_i) - \tilde{L}_i(H_0, f_i, z_i)]^2}{\Delta_{L,i}^2 + \Delta_{\tilde{L},i}^2}, \quad (4)$$

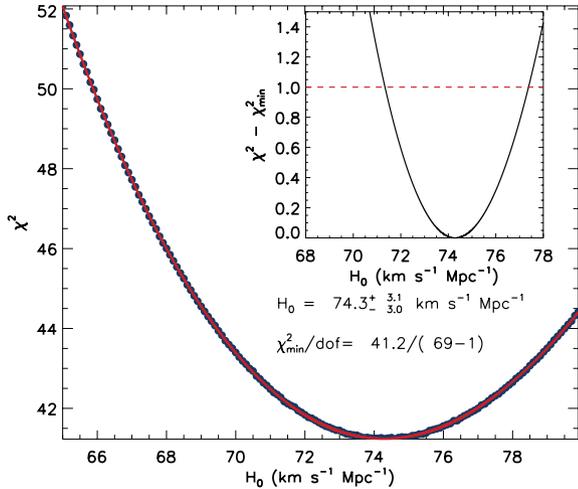
where the summation is over the H II galaxies,  $\sigma_i$  are the measured velocity dispersions (equation 1),  $L_i(\sigma)$  are the luminosities estimated from the ‘distance indicator’ as defined in equation (3),  $\Delta_{L,i}$  are their errors propagated from the uncertainties in  $\sigma$  and the slope and intercept of the relation.  $\tilde{L}_i(H_0, f_i, z_i)$  are the luminosities obtained from the measured fluxes and redshifts by using a particular value of  $H_0$  in the Hubble law to estimate distances, and  $\Delta_{\tilde{L},i}$  are the errors in this last estimation of luminosities, propagated from the uncertainties in the fluxes and redshifts.

Fig. 3 shows the resulting  $\chi^2$  for the range of  $H_0$  values used, with the solid line being a cubic fit to the points. The  $1\sigma$  confidence limits of  $H_0$  were obtained from the values for which  $\chi^2 - \chi_{\text{min}}^2 = 1$  since the fit has only one degree of freedom (see the inset panel in Fig. 3).

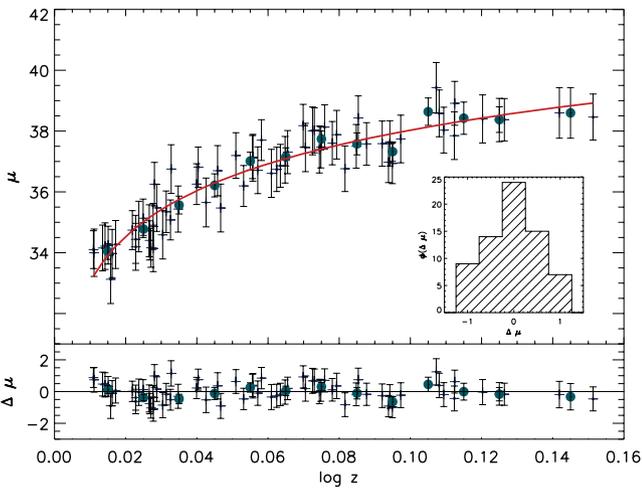
The value obtained for  $H_0$  using the above described procedure is

$$H_0 = 74.3_{-3.0}^{+3.1} \text{ km s}^{-1} \text{ Mpc}^{-1}. \quad (5)$$

<sup>1</sup> We have verified that the initial choice for the value of  $H_0$  does not alter the determined slope value.



**Figure 3.** Values of  $\chi^2$  for the grid of  $H_0$ . The solid line is a cubic fit to the points. The inset panel shows the value of  $\chi^2 - \chi^2_{\min}$ .



**Figure 4.** Hubble diagram for our sample of 69 H II galaxies. The thick points are the mean values for bins of 0.01 in redshift. The solid line shows the run with redshift of the distance modulus for  $H_0 = 74.3$ . Residuals are plotted in the bottom panel and their distribution is shown in the inset. The rms value is 0.57 mag.

Fig. 4 shows the Hubble diagram for the sample of H II galaxies used for the  $H_0$  value determination. The continuous line shows the redshift run of the distance modulus, obtained from the linear Hubble law and the fitted  $H_0$  value, whereas the points correspond to the individual H II galaxy distance moduli obtained through the  $L(H\beta)$ – $\sigma$  correlation.

The quoted Hubble constant uncertainty in equation (5) reflects only the random errors, while systematic errors can also affect the mean value as well as the overall  $H_0$  uncertainty. We have identified as potential sources of systematic errors the following: (a) the broadening of the emission lines, being contaminated by a rotational velocity component; (b) the internal structure/multiplicity of GEHR and H II galaxies; (c) stellar winds affecting the line profiles; (d) internal extinction; (e) coherent or peculiar motions affecting the redshifts of nearby H II galaxies; (f) the age of GEHR and H II galaxies; (g) the Malmquist bias and (h) variations in the initial mass function (IMF). The detailed discussion of these systematics is an important aspect of the  $H_0$  determination and will be presented in a

**Table 1.** Systematic error budget on the  $H_0$  determination.

Symbol	Source	Error (km s <sup>-1</sup> Mpc <sup>-1</sup> )
$\sigma_{a, b}$	Rotation, multiplicity	0.7
$\sigma_c$	Stellar winds	1.1
$\sigma_d$	Internal extinction	0.7
$\sigma_f$	Object’s age	1.4
$\sigma_g$	Malmquist bias	2.1
$\sigma_h$	IMF	–
Total		2.9

future paper (Chávez et al., in preparation). Here we briefly discuss these systematics, and the procedures used to minimize them.

(a, b) To minimize the rotation and multiple component systematic effect, we have used in our correlation only those objects with emission line profiles that are Gaussian and show no multiple components (for a discussion, see Bosch et al. 2002).

(c) The presence of weak extended (non-Gaussian) wings in the emission line profiles introduces a small systematic effect. These weak wings are probably associated with stellar winds. The resulting effect is that, taking into account the wings in the fit, the final full width at half-maximum tends to be slightly smaller. This should affect similarly both GEHR and H II galaxies. We estimate that this may introduce a systematic error of about 2 per cent in  $H_0$ .

(d) The extinction has always been estimated using the Balmer decrement method. We do not expect a sizeable systematic effect associated with this correction.

(e) H II galaxies tend to populate the voids, so local peculiar motions should be relatively small. Furthermore, to minimize the effects of coherent bulk flows on the redshifts of the H II galaxies, we imposed a lower radial velocity limit of 3000 km s<sup>-1</sup>. In any case, we have also computed  $H_0$  including a local bulk flow correction and found no overall effect.

(f) The age of the GEHR and H II galaxies affects their mass-to-light ratio ( $M/L$ ) and therefore the zero-point of the  $L(H\beta)$ – $\sigma$  relationship. To minimize this effect, we have specifically selected objects with  $W(H\beta) > 50 \text{ \AA}$ . This guarantees that the age of the star-forming region is less than 6 Myr, thus minimizing the effect of evolution (Leitherer et al. 1999). We estimate that at most a plausible systematic difference in ages between GEHR and H II galaxies may affect  $H_0$  at a 2 per cent level.

(g) We have calculated the Malmquist bias following the procedure proposed by Giraud (1987) adopting a power-law luminosity function, with a slope  $\alpha = -1.7$ . We have obtained a value of 2.1 km s<sup>-1</sup> Mpc<sup>-1</sup> at  $z = 0.16$ , which we consider as one of the systematic error components.

(h) The  $L(H\beta)$ – $\sigma$  distance estimator relies on the universality of the IMF. Any systematic variation in the IMF will affect directly the  $M/L$  and therefore the slope and zero-point of the relation. The fact that our estimates of the Hubble constant are in agreement with those from SN Ia supports the hypothesis of a universal IMF.

Table 1 shows the systematic error budget on the  $H_0$  determination.

## 4 CONCLUSIONS

It is indisputable that in the epoch of intense studies aimed at measuring the dark energy equation of state, it is of paramount importance to minimize the amount of priors needed to successfully complete such a task. One such prior is the Hubble constant  $H_0$  and

its measurement at the  $\sim 1$  per cent accuracy level has been identified as a necessary prerequisite for putting effective constraints on the dark energy, on neutrino physics and even on tests, at cosmological scales, of general relativity (see Suyu et al. 2012). Furthermore, it is highly desirable to have independent determinations of  $H_0$ , since this will help understand and control systematic effects that may affect individual methods and tracers of the Hubble expansion.

It is within this latter strategy that our current work falls. We have carried out VLT and Subaru observations of a sample of nearby H II galaxies identified in the SDSS DR7 catalogue and 2-m class telescopes spectrophotometry, in order to define their  $L(H\beta)-\sigma$  correlation, which we use to estimate the value of the Hubble constant. This is achieved by determining the zero-point of the distance indicator using GEHR in nearby galaxies, for which accurate independent distance measurements exist (based on Cepheids, RR Lyrae, TRGB and eclipsing binaries).

Using our sample of 92 objects (69 H II galaxies with  $z \lesssim 0.16$  and 23 GEHR in nine galaxies with distances determined via primary indicators), we obtain

$H_0 = 74.3 \pm 3.1(\text{random}) \pm 2.9(\text{systematic}) \text{ km s}^{-1} \text{ Mpc}^{-1}$ , in excellent agreement with, and independently confirming, the recent SNe Ia-based results of Riess et al. (2011).

#### ACKNOWLEDGMENTS

The authors thank the support by VLT, Subaru, San Pedro Mártir and Cananea Observatories staff and the hospitality of the Departamento de Física Teórica of the Universidad Autónoma de Madrid, where part of this work was done. RC, RT, ET and MP acknowledge the Mexican Research Council CONACYT for financial support through grants CB-2005-01-49847, CB-2007-01-84746 and CB-2008-103365-F. FB acknowledges partial support from the National Science Foundation grants AST-0707911 and AST-1008798. SB and RT acknowledge financial support from the Spanish Ministry of Education, within the programme of Estancias de Profesores e Investigadores Extranjeros en Centros Españoles (SAB2010-0118 and SAB2010-0103). We thank the anonymous referee whose suggestions greatly improved the clarity of this Letter.

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