Determining the Hubble constant using Giant extragalactic HII regions and HII galaxies

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5 May 2014

ABSTRACT

We report the first results of a long term program aiming to provide accurate independent estimates of the Hubble constant ($H_0$) using the $L(H\beta) - \sigma$ distance estimator for Giant extragalactic HII regions (GEHR) and HII galaxies.

We have used VLT and Subaru high dispersion spectroscopic observations of a local sample of HII galaxies, identified in the SDSS DR7 catalogue in order to redefine and improve the $L(H\beta) - \sigma$ 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 HII galaxies and 23 GEHR in 9 galaxies we obtain $H_0 = 74.3\pm 3.1$ (statistical)$\pm 2.9$ (systematic) km s$^{-1}$Mpc$^{-1}$, in excellent agreement with, and independently confirming, the most recent SNe Ia based results.

Key words: cosmology:distance scale, cosmological parameters; ISM:HII regions

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; Tamman, Sandage & Reindl 2008; Freedman & Madore 2010). In particular, the use of SNe Ia to measure the Hubble constant has a long history in astronomy (eg., Sandage & Tammann 1982; 1990). The subsequent discovery of the correlation between the magnitude at peak brightness and the rate at which it declines thereafter (eg., 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, like the Large Magellanic Cloud (LMC), Galactic Cepheids, the “maser” galaxy NGC 4258, etc. (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 HST Calibration program (Saha et al. 2001; Sandage et al. 2006) who 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) who furnished a value of $H_0 = 72 \pm 2 \text{(random)} \pm 7 \text{(systematic)}$ km s$^{-1}$ Mpc$^{-1}$, based on Cepheid distances of external galaxies and the LMC as the first rung 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 $H_0 = 73 \pm 2 \text{(random)} \pm 4 \text{(systematic)}$ km s$^{-1}$ Mpc$^{-1}$ (see Freedman & Madore 2010). Tammann et al. (2000) used a variety of local calibrators to recalibrate the SNe Ia and found a significantly lower value of $H_0 = 62.3 \pm 4$ km s$^{-1}$ Mpc$^{-1}$. The difference has since been explained as being due to a variety of external causes among which the use of heavily reddened Galactic Cepheids and of less accurate photographic data (Riess et al. 2000a,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: $H_0 = 73.8 \pm 2.4$ km s$^{-1}$ 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 ($0 \leq z \leq 1.5$). Therefore, due to the great importance of direct determinations of the Hubble constant for cosmological studies (e.g., Suyu et al. 2010) 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, that indeed is what they are, hence their name. Their similarity with 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 and 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. $W(H_{\beta}) > 50$ Å.

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 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 increases. This induces a correlation between the luminosity of recombination lines, e.g. $L(H_{\beta})$ and the ionized gas velocity dispersion $\sigma$ (see Terlevich & Melnick 1981; Hippeltein 1986; Melnick, Terlevich & Moles 1988; Melnick, Terlevich & Terleverich 2000; Fuentes-Masip et al. 2000; Telles et al. 2001, Bosch et al. 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, Terlevich & Moles (1988). The use of H II galaxies as deep cosmological tracers was discussed by Melnick, Terlevich & Terlevich (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 paper is to use H II galaxies and a local calibration of the $L(H_{\beta}) - \sigma$ 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 ($D < 5$ arcsec), having large Balmer emission line fluxes and equivalent widths. A lower limit for the equivalent width of $H_{\beta}$ of 50 Å was chosen to avoid starbursts that are either evolved or contaminated by an underlying older stellar population component (cf. Melnick, Terlevich & Terlevich 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 $L(H_{\beta}) - \sigma$ relation obtained from previous work, high-resolution echelle spectroscopy for the H II galaxy sample was performed at 8 meter class telescopes. We used the Ultraviolet and Visual Echelle Spectrograph (UVES) (Dekker et al. 2000) at the European Southern Observatory (ESO) 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 (NAOJ) Subaru Telescope on Mauna Kea, Hawaii. The chosen setups provided UVES spectra centred at 5800 Å with a slit-width of 2′′, giving a spectral resolution of ∼22000. The HDS spectra were centred at ∼5400 Å, with a slit width of 4′′ the spectral resolution obtained was ∼9000.

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

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 $H_0$. 

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Hβ and [O III] λλ4959, 5007 line widths were measured fitting single gaussians to the line profiles. As previously found most HII galaxies show line profiles that are well fitted by single gaussian (e.g. Melnick et al. 1988, Bordalo & Telles 2011). We cleaned the sample by first removing from the original list those HII galaxies with either asymmetric or double/multiple line profile. We also removed those HII galaxies showing rotation or large photometric errors in their Hβ fluxes or with an uncertain reddening correction. All this reduced the sample from 128 to 69 HII galaxies.

The values of the observed velocity dispersions, σobs, were corrected for thermal (σt) and instrumental (σi) broadening, and the final corrected dispersion was estimated according to:

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

The 1σ uncertainties of the velocity dispersion were estimated from multiple observations computing the variance over the repeated measurements; otherwise as the mean value of the obtained relative errors.

Hβ integrated fluxes were measured by fitting a single gaussian to the long slit spectra, while their 1σ uncertainties were estimated from the expression (e.g. Tresse et al. 1999):

\[ \sigma_F = \sigma_o D(2N_{pix} + W/D)^{1/2}, \] (2)

where σo is the mean standard deviation per pixel of the continuum on each side of the line, D is the spectral dispersion, Npix 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 and DR8 spectroscopic data when available, otherwise from our echelle data or the Spectrophotometric Catalog of HII 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 and Plionis (1998). The 1σ uncertainties were propagated using a Montecarlo procedure.

To determine the zero point for the L(Hβ) – σ relation, we obtained data from the literature for a sample of 23 GEHR in 9 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 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 (μ) are listed as an inset in Figure 1. The global integrated Hβ fluxes and corresponding extinction were obtained from the values reported by Melnick et al. (1987).

3 DETERMINATION OF H₀

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

(i) First we determine the slope of the L(Hβ) – σ relation for HII galaxies. Since the slope is independent of H₀ we use an arbitrary value of H₀ to determine luminosities from the observed Hβ flux and the Hubble distance.

(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 one, i.e., that based on HII galaxies. Figure 1 shows the L(Hβ) – σ relation for the GEHR sample. The slope of the correlation has been fixed to the value obtained from the HII galaxies sample fitting in (i).

The resulting L(Hβ) – σ correlation for the joint sample of GEHR and HII galaxies is:

\[ \log_{10} L(H\beta) = (4.97 \pm 0.10) \log_{10} \sigma + (33.25 \pm 0.15) \] (3)

1 We have verified that the initial choice for the value of H₀ does not alter the determined slope value.
internal extinction, (e) coherent or peculiar motions affect the internal structure/multiplicity of GEHR and H II lines, being contaminated by a rotational velocity component. We have identified as potential sources of systematic effects in the fluxes and redshifts, propagated from the uncertainties in the fluxes and redshifts by using a particular value of $H_0$ in the Hubble law to estimate distances, and $\Delta L, i$ are the errors in this last estimation of luminosities, propagated from the uncertainties in the fluxes and redshifts.

Figure 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 1σ confidence limits of $H_0$ were obtained from the values for which $\chi^2 - \chi^2_{\text{min}} = 1$ since the fit has only one degree of freedom (see the inset panel in Figure 3).

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

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

Figure 4 shows the 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 r.m.s. value is 0.57 mag.

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 $\chi^2 - \chi^2_{\text{min}}$.

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 r.m.s. value is 0.57 mag.
Table 1. Systematic error budget on the $H_0$ determination

| Symbol | Source                  | Error (km s$^{-1}$ Mpc$^{-1}$) |
|--------|-------------------------|---------------------------------|
| $\sigma_{a,b}$ | 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                             |
| $\sigma_b$      | IMF                     | —                               |
| **Total**       |                         | **2.9**                         |

in ages between GEHR and HII galaxies may affect $H_0$ at a 2% 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$^{-1}$ Mpc$^{-1}$ 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 ratio 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 $\sim 1\%$ 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 HII galaxies identified in the SDSS DR7 catalogue and 2m 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 HII galaxies with $z \lesssim 0.16$ and 23 GEHR in 9 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).

ACKNOWLEDGEMENTS

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. S.B. and RT acknowledge financial support from the Spanish Ministry of Education, within the program 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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