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

Ricardo Chávez[1], Elena Terlevich[1*], Roberto Terlevich[1,2] $\star$, Manolis Plionis[1,3], Fabio Bresolin[4], Spyros Basilakos[5,6] and Jorge Melnick[7]

[1] *Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, Mexico*
[2] *Institute of Astronomy, University of Cambrige, Cambridge, UK*
[3] *Institute of Astronomy & Astrophysics, National Observatory of Athens, Thessio 11810, Athens, Greece*
[4] *Institute for Astronomy, University of Hawaii, Honolulu, Hawaii, USA*
[5] *Academy of Athens Research Center for Astronomy & Applied Mathematics, Soranou Efessiou 4, 11-527 Athens, Greece*
[6] *High Energy Physics Group, Dept. ECM, Universitat de Barcelona, Av. Diagonal 647, E-08028 Barcelona, Spain*
[7] *European Southern Observatory, Santiago de Chile, Chile*

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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 $L(\text{H}\beta) - \sigma$ distance estimator for Giant extragalactic H II regions (GEHR) and H II galaxies.

We have used VLT and Subaru high dispersion spectroscopic observations of a local sample of H II galaxies, identified in the SDSS DR7 catalogue in order to re-define 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 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:H II 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; 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 (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

$\star$ Visiting Professor UAM, Madrid

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. (2008) used a variety of local calibrators to recalibrate the SNe Ia and found a significantly lower value of $H_0 = 62.3 \pm 4$ 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. 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: $H_0 = 73.8 \pm 2.4$ 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 ($0 \lesssim z \lesssim 1.5$). Therefore, due to the great importance of direct determinations of the Hubble constant for cosmological studies (eg., 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, 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 emphasise 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(Hβ) > 50Å.

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. $L(\text{H}\beta)$ and the ionized gas velocity dispersion σ (see Terlevich & Melnick 1981; Hippelein 1986; Melnick, Terlevich & Moles 1988; Melnick, Terlevich & Ter-

levich 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 $L(\text{H}\beta) - \sigma$ 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 ($D < 5$ arcsec), having large Balmer emission line fluxes and equivalent widths. A lower limit for the equivalent width of Hβ 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 $L(\text{H}\beta) - \sigma$ 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 $\sim$ 22000. The HDS spectra were centred at $\sim$ 5400 Å, and with a slit width of 4″ the spectral resolution obtained was $\sim$ 9000.

To obtain accurate total Hβ 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 HII 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.

Hβ and [O III] $\lambda\lambda$4959, 5007 line widths were measured fitting single gaussians to the line profiles. As previously found most H II 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 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 Hβ fluxes or with an uncertain reddening correction. All this reduced the sample from 128 to 69 H II galaxies.

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

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

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):

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

where σ_c is the mean standard deviation per pixel of the continuum on each side of the line, D is the spectral dispersion, N_{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 and DR8 spectroscopic data when available, otherwise from our echelle data or the Spectrophotometric Catalog 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 and Plionis (1998). The 1σ uncertainties were propagated using a Montecarlo 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 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 H_0

The procedure we use to estimate the Hubble constant comprises three steps:
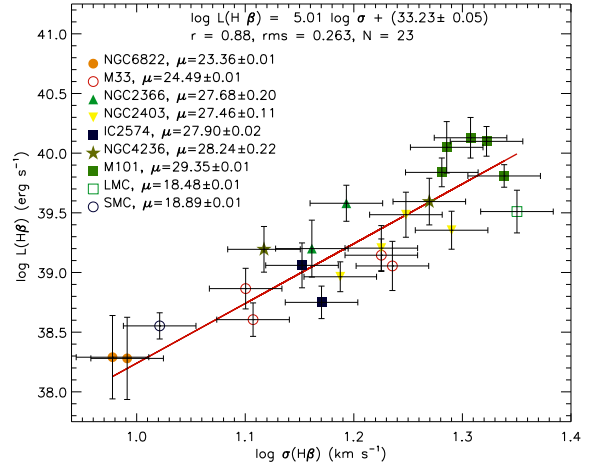
Figure 1. $L(\text{H}\beta) - \sigma$ relation for the GEHR sample. The correlation parameters and the adopted individual distance moduli are given in the inset. The line is the best fit for the slope determined by the fit to the HII galaxies (see Eq. 3).
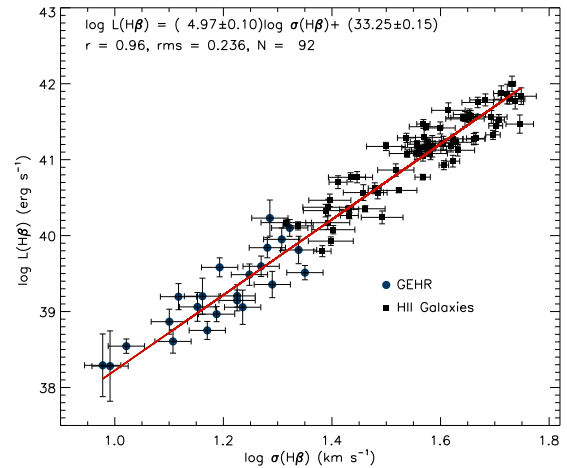
Figure 2. $L(\text{H}\beta) - \sigma$ relation for the joint H II galaxies and GEHR samples. The least square fit considers the errors in both axes.

(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 arbitary value of H_0 to determine luminosities from the observed Hβ flux and the Hubble distance[1].

(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 H II galaxies. Figure 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:

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

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[1] We have verified that the initial choice for the value of H_0 does not alter the determined slope value.
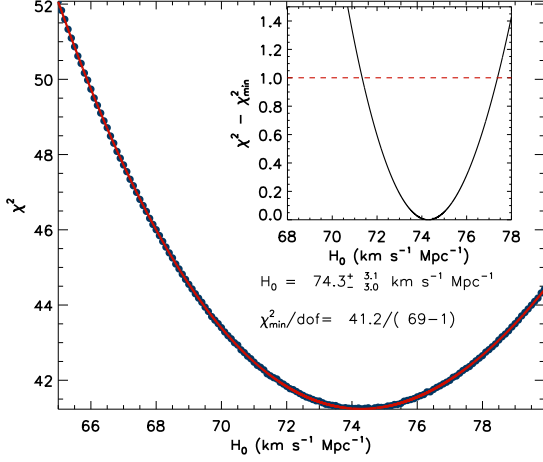
Figure 3. Values of χ^2 for the grid of H_0. The solid line is a cubic fit to the points. The inset panel shows the value of $\chi^2 - \chi^2_{min}$.

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 r.m.s. value is 0.57 mag.

has r.m.s. $\log_{10} L(H\beta) = 0.236$ and is shown in figure 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, σ_i are the measured velocity dispersions (eq. 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 σ and the slope and intercept of the relation. $\tilde{L}_i(H_o, f_i, z_i)$ 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.
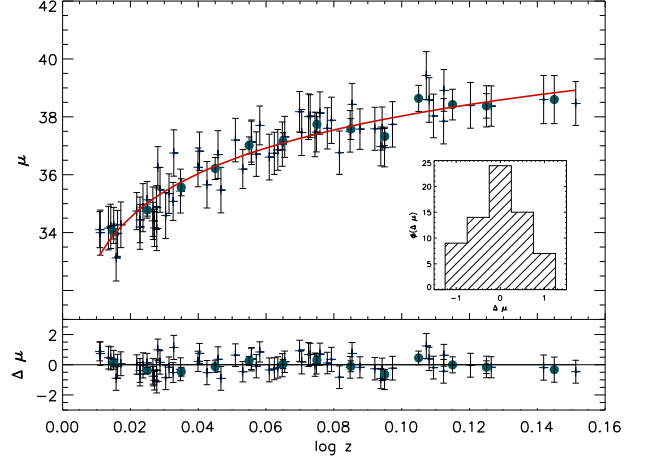
Figure 3 shows the resulting χ^2 for the range of H_0 values used, with the solid line being a cubic fit to the points. The 1σ confidence limits of H_0 were obtained from the values for which $\chi^2 - \chi^2_{min} = 1$ since the fit has only one degree of freedom (see the inset panel in Figure 3).

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

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

Figure 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 affect-

ing the redshifts of nearby H II galaxies, (f) the age of GEHR and H II galaxies, (g) the Malmquist bias, (h) variations in the IMF. The detailed discussion of these systematics is an important aspect of the H_0 determination and will be presented in a future paper (Chávez et al. in preparation). Here we briefly discuss these systematics, and the procedures used to minimize them.

(a) and (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 FWHM 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 percent in H_0.

(d) The extinction has been always 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. 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 M/L ratio and therefore the zero point of the $L(H\beta) - \sigma$ relationship. To minimize this effect we have specifically selected objects with $W(H\beta) > 50$ Å. 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

Table 1. Systematic error budget on the H_0 determination

Symbol	Source	Error (km s^{-1} Mpc^{-1})
σ_a, b	Rotation,Multiplicity	0.7
σ_c	Stellar Winds	1.1
σ_d	Internal Extinction	0.7
σ_f	Object's Age	1.4
σ_g	Malmquist Bias	2.1
σ_h	IMF	—-
Total		2.9

in ages between GEHR and H II 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 $L(\text{H}\beta) - \sigma$ 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 H II galaxies identified in the SDSS DR7 catalogue and 2m class telescopes spectrophotometry, in order to define their $L(\text{H}\beta) - \sigma$ 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 9 galaxies with distances determined via primary indicators) we obtain:
$H_0 = 74.3 \pm 3.1(\text{random}) \pm 2.9 \text{ (systematic) km s}^{-1} \text{ Mpc}^{-1}$,
in excellent agreement with, and independently confirming, the recent SNe Ia-based results of Riess et al. (2011).

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